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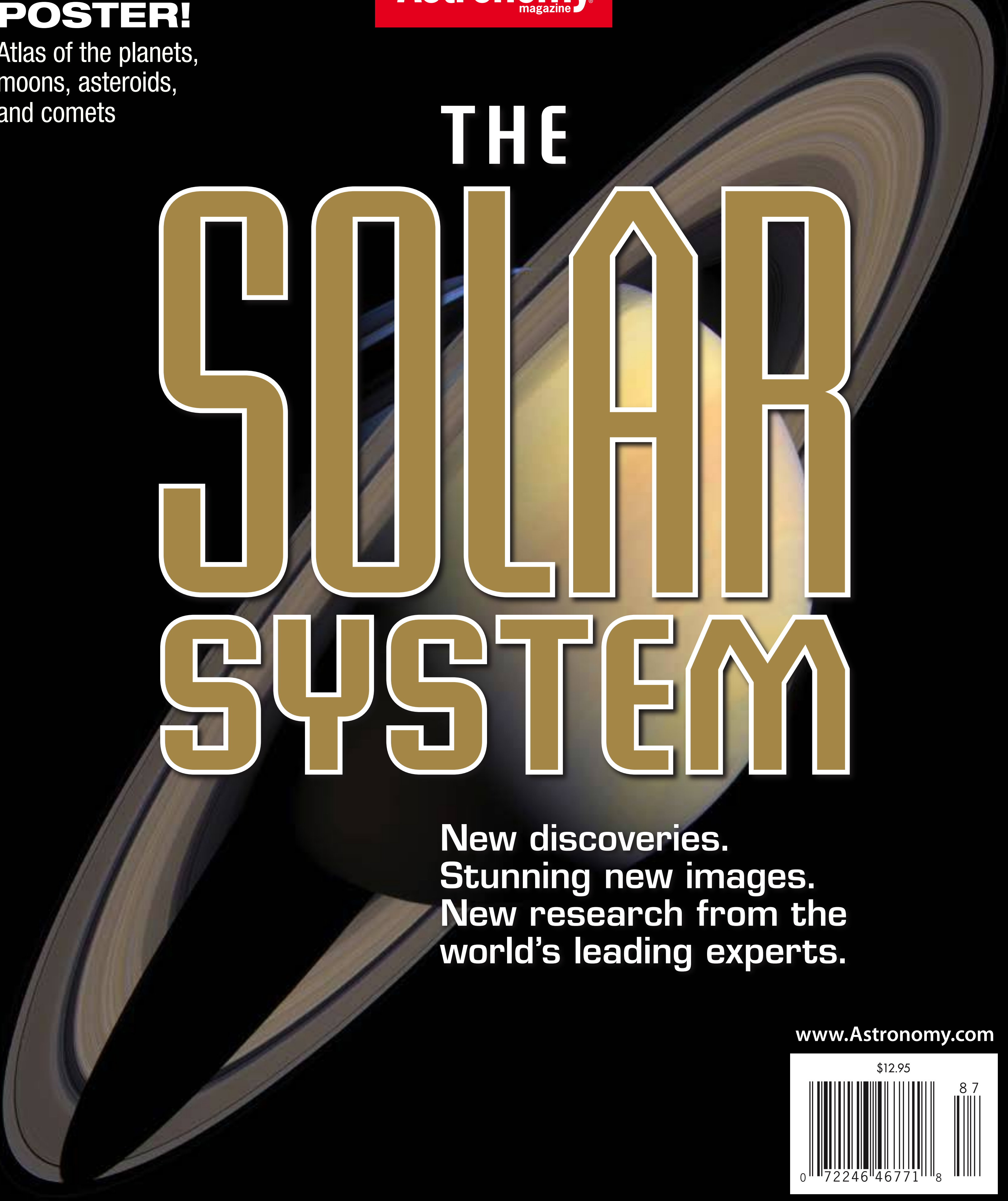

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Everything you've ever wanted to know about the solar system

Thirty years ago, astronomers knew little about how the solar system worked. Then, in 1979, Voyager 1 reached Jupiter on the first leg of its "grand tour," which would carry it past Saturn. Its sister-craft, Voyager 2, would reach Uranus and Neptune. Over the following several years, NASA executed the most significant step in exploring the solar system up to that time, one that revolutionized astronomers' knowledge of the planets.

During the 20 years that followed the success of the Voyagers, many other spacecraft explored the solar system. Magellan and Venus Express mapped Venus. Galileo went to Jupiter. Cassini-Huygens set off for Saturn. Mars received an array of invaders, from Mars Pathfinder to Mars Global Surveyor to the Mars Reconnaissance Orbiter to Spirit and Opportunity to Phoenix. NEAR-Shoemaker touched down on an asteroid. An array of instruments studied the Sun. As a result, planetary scientists have watched an explosion in the volume of information they have about the solar system and how it works. The outcome is that their understanding of our home in the galaxy is growing by the minute.

The editors of *Astronomy* magazine have worked hard to collect the most important results about our cosmic home in this special edition, *The Solar System*. In these 105 editorial pages, we've packed entertaining explanations of the latest science, great photographs from spacecraft, and informative illustrations that will help you understand the most recent findings on our Sun and its family of planets.

We're also proud to have a stellar lineup of contributors to this issue. They represent the leading lights of the planetary science field.

Longtime friend and contributor William K. Hartmann of the Planetary Science Institute has written an overview of the solar system's origin. Another frequent contributor, Sten Odenwald of Catholic University of Washington, delivers a spectacular story about solar research. The innermost planet, Mercury, receives full analysis by Clark R. Chapman of the Southwest Research Institute in Boulder, Colorado. One of the foremost authorities on Venus, James W. Head III of Brown University, delivers an up-to-the-minute assessment of our so-called sister planet.

Next up is the home world, Earth. Jonathan Lunine of the University of Arizona tells how scientists' knowledge of our planet has changed over the last few years. That favorite target of beginning skygazers, the Moon, receives its due from Peter Schultz of Brown University. And Alfred McEwen of the University of Arizona captures Mars in its full splendor.

Who could understand the solar system without gas giants? Typically, Saturn entices us to become astronomy enthusiasts in the first place. John Spencer of the Southwest Research Institute in Boulder gives us the story on Jupiter, while Saturn gets the treatment by William B. McKinnon of Washington University in St. Louis. Heidi B. Hammel of the Space Science Institute describes Uranus and Neptune.

Pluto and the other Kuiper Belt objects receive the analytical scrutiny of S. Alan Stern, principal investigator of the New Horizons Mission. Henry H. Hsieh of Queen's University, Belfast, describes the nuts and bolts of comets and asteroids. David A. Kring of the University of Arizona tells us all about meteorites, and Timothy E. Dowling of the University of Louisville compares planetary atmospheres.

We've also included a helpful story about how to observe planets from your backyard by *Astronomy* Senior Editor Michael E. Bakich. A fascinating pullout poster of the solar system and its components was produced by *Astronomy* Senior Editor Rich Talcott and Illustrator Roen Kelly. It's a treasure trove of information and images like no other. We know you'll refer to it again and again in the future. Enjoy!

Yours truly,

David J. Eicher
Editor

THE
SOLAR
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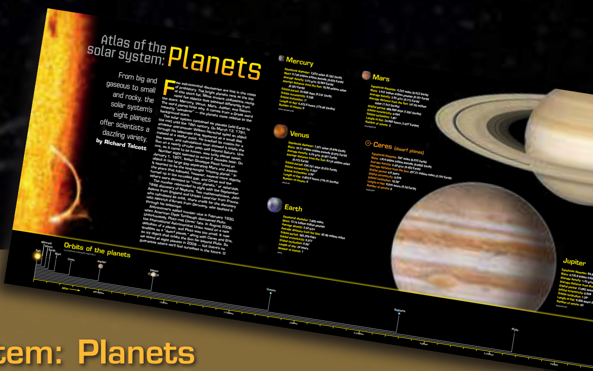

POSTER ►
Atlas of the solar system: Planets
From big and gaseous to small and rocky, the solar system's eight planets offer scientists a dazzling variety.
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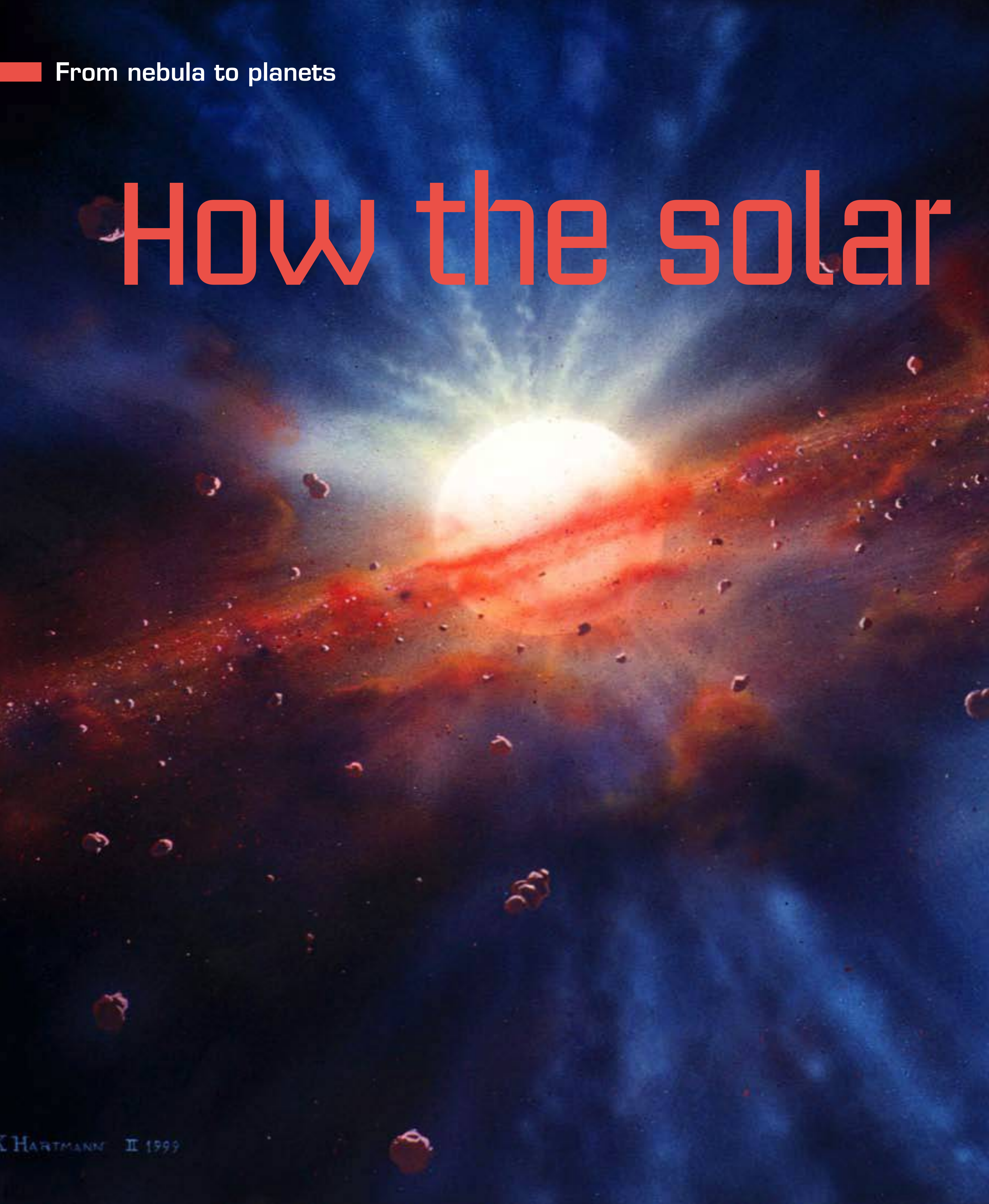
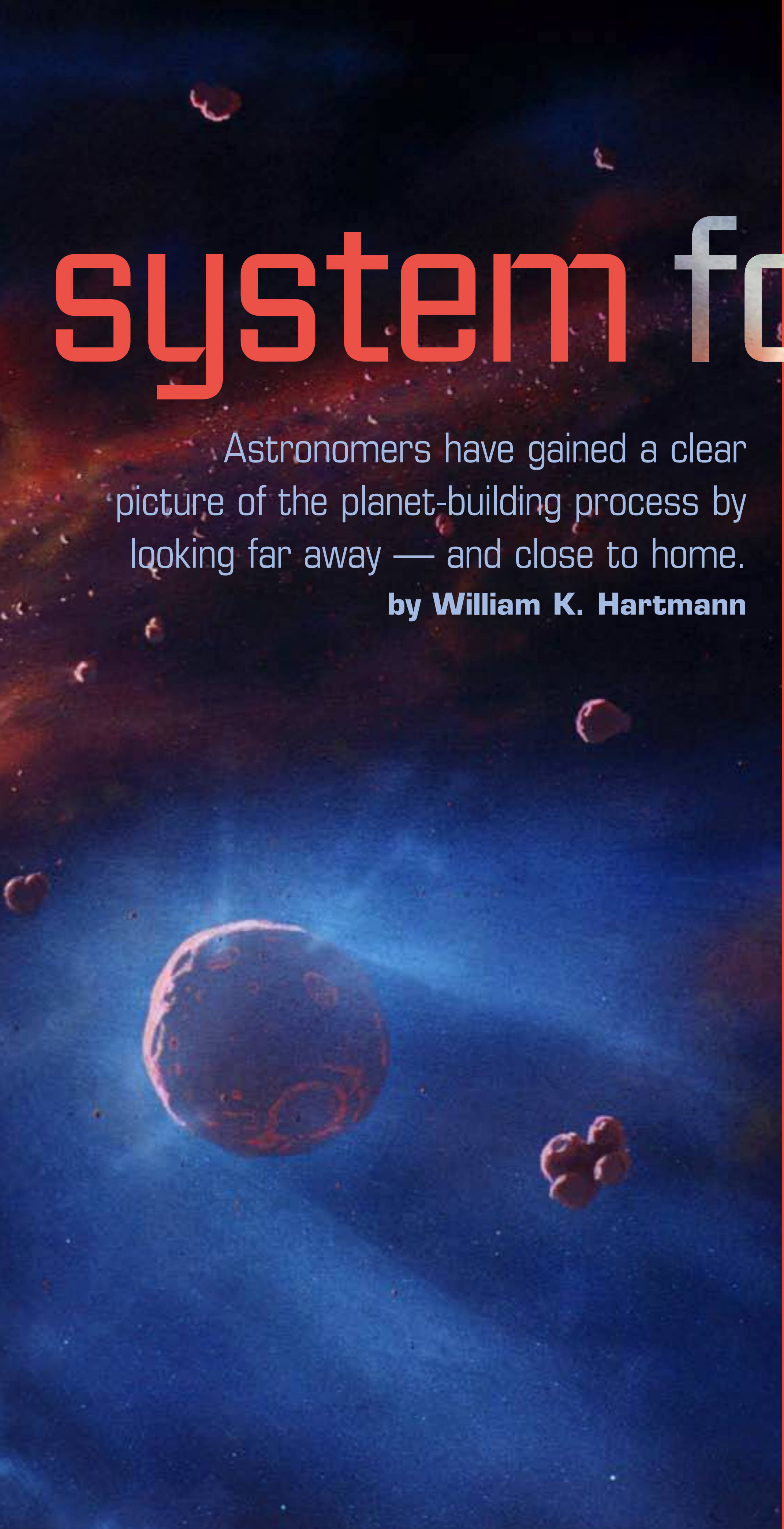
How the solar


K Hartmann II 1999

system formed

Astronomers have gained a clear picture of the planet-building process by looking far away — and close to home.

by William K. Hartmann



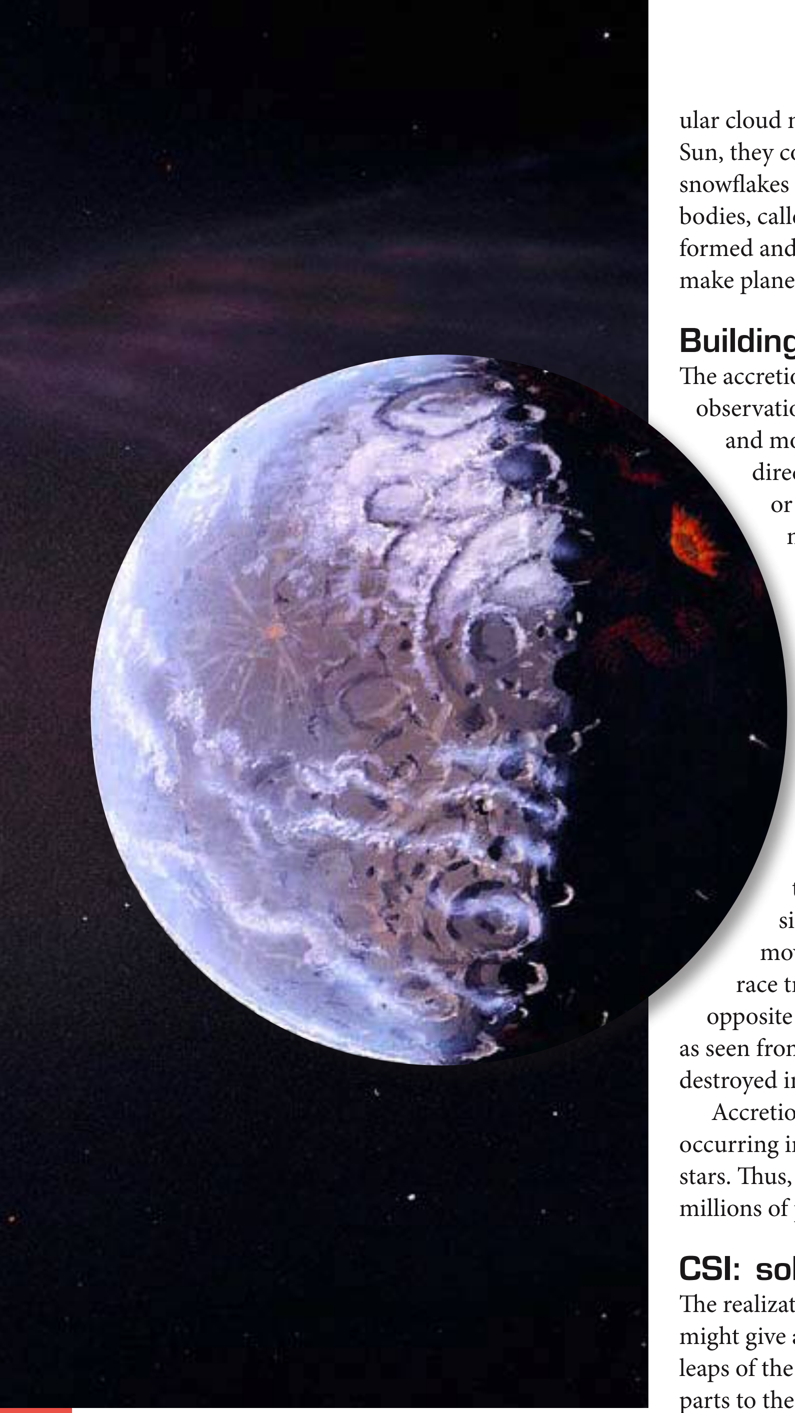
“To trace the origin of the solar system is archaeology, not physics,” said Nobel Laureate and Swedish astrophysicist Hannes Alfvén (1908–1995). He spent years studying clues to the solar system’s birth.

Researching the solar system’s origin involves ancient relics, such as meteorites, lunar rocks, and martian rocks. Studying the solar system also requires planetary scientists to interpret ancient orbital “footprints” — planets revolving and spinning in a disk-shaped star system.

Since the time Alfvén and other pioneers worked, around 1960, one dramatic change has occurred. We no longer have only one “archaeological site.” In the 1960s, astronomers found newly forming stars surrounded by nebulae containing silicate dust and ice grains — the material from which planets form.

By the 1990s, scientists had discovered planets orbiting other stars. Today, our attempt to understand the solar system’s formation involves two main lines of research: first, the

◄ TERRESTRIAL PLANETS FORMED as gas, dust, and debris stuck together when the growing bodies swept them up. This illustration shows how the early solar system may have appeared. WILLIAM K. HARTMANN



EARTH FORMED out of the solar nebula, a disk-shaped mass of gas and dust, during a brief planet-building period some 4.5 billion years ago. Our home planet took shape as smaller bodies collided and stuck together. WILLIAM K. HARTMANN

material in our own system; and, second, observations of planet-forming material around other stars.

Data from these two streams merge into a consistent picture. The result is that our own solar system formed about 4.56 billion years ago, during a brief planet-building period lasting a few tens of millions of years.

Planets, dwarf planets, asteroids, and comets apparently grew when many small bodies clumped together, or accreted, into a few larger bodies. As dust grains in the nebular cloud moved around the primordial Sun, they collided and stuck together like snowflakes in a winter storm. Asteroid-like bodies, called planetesimals, gradually formed and eventually slammed together to make planets.

Building a solar system

The accretion process explains a number of observations. The planets, dwarf planets, and most asteroids orbit in the same direction around the Sun ("prograde," or counterclockwise, as seen from north of their orbital planes). This common motion is a result of the solar system growing from a single nebula in which particles moved that direction, like cars on a race track. A planetesimal moving the opposite way ("retrograde," or clockwise as seen from above) would soon have been destroyed in a high-speed, head-on collision.

IN THE 20TH CENTURY, RADIOACTIVE ISOTOPES CONFIRMED THE SUN AND PLANETS FORMED ABOUT 4.5 BILLION YEARS AGO.

Accretion seems to be a natural process occurring in dusty nebulae around young stars. Thus, our solar system may be one of millions of planetary systems in our galaxy.

CSI: solar system

The realization that direct observations might give answers was one of the great leaps of the Renaissance. There were two parts to the problem: How did the solar system arise, and when did it happen?

Research during the 1600s — including observations by Italian astronomer Galileo Galilei (1564–1642) in 1610, and the laws of gravity and motion pioneered by English physicist Sir Isaac Newton (1643–1727) in the 1680s — set the stage for analyzing the "how." The planetary system's origin could be approached purely from direct physical principles, rather than speculation.

Galileo, Newton, and others created a framework in which natural laws could be used to analyze the history and properties of natural systems — whether falling bodies, gas atoms in a bottle, or planets moving around the Sun.

Fledgling naturalists of the 1600s and 1700s debated two main, conflicting views about the origin process. The so-called catastrophist view suggested dramatic, low-probability events created the solar system.

Around 1778, the French naturalist Georges-Louis Leclerc de Buffon (1707–1788) theorized that a gigantic comet passed close to the Sun and threw out planet-forming material. Because such collisions are rare, scientists expect planetary systems rarely form this way.

The second, evolutionary view proposed planet formation might be a more common side effect of star formation. For example, in 1755, German philosopher Immanuel Kant (1724–1804) suggested debris surrounding the newly formed Sun might aggregate.

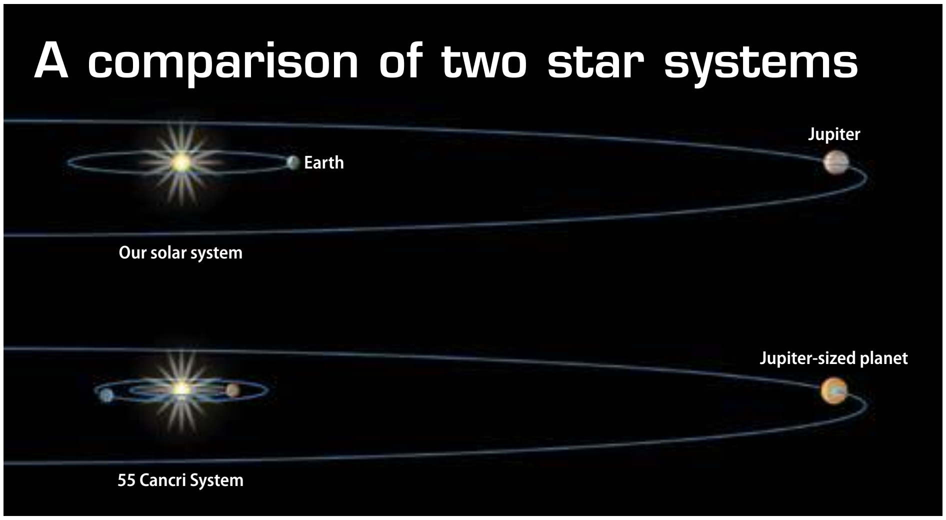
Around 1795, French mathematician and astronomer Pierre-Simon Laplace (1749–1827) extended this idea. Laplace surmised that, shortly after the Sun formed, it cooled, contracted, spun faster, and threw off rings of hot material that then formed a disk-shaped nebula — the placenta from which the planets grew.

The so-called Kant-Laplace nebular hypothesis predates current theory that a disk-shaped nebula of gas and dust, called the solar nebula, surrounded the primeval Sun. In the 1950s and 1960s, Soviet and American theorists analyzed particle movements within the solar nebula.

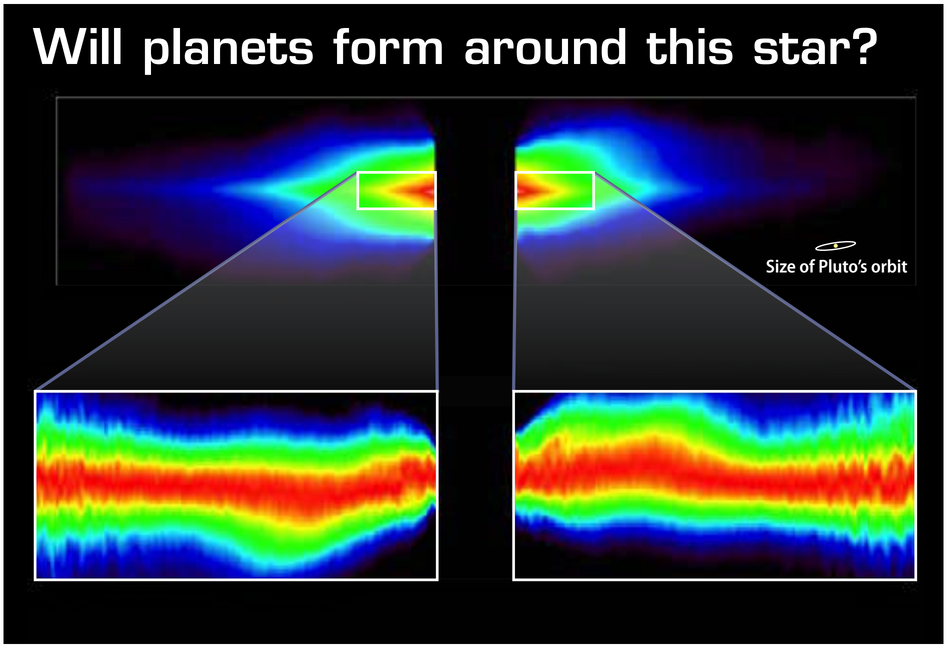
Leading figures were Soviet astronomer Victor Safronov (1917–1999) in the 1950s and American planetary-formation theorist George Wetherill (1925–2006) in the 1960s. Their mathematical analysis of accretion tracked how planetesimals would collide and aggregate in the solar nebula.

The larger the body, the greater its cross-section for sweeping up nearby particles. Once the body became massive enough, gravity helped it attract even more matter. Thus, in any given doughnut-shaped zone around the Sun, the largest body underwent "runaway" growth and eventually swept up everything else in its zone.

William K. Hartmann *is a senior scientist at the Planetary Science Institute in Tucson, as well as a writer and painter.*



▲ **A JUPITER-SIZED PLANET** orbits Sun-like star 55 Cancri, located about 41 light-years from Earth in the constellation Cancer. Astronomers have yet to discover whether planetary systems that form Jupiter-sized planets close to their host stars are similar to our solar system. This system's proximity to Earth makes it a good place to search for clues. NASA


Will planets form around this star?
Size of Pluto's orbit

▲ **SILICATE DUST AND ICE PARTICLES** girdle the 69-light-year-distant star Beta Pictoris. These planet-building materials may be in the process of accreting. This process likely formed the planets in our solar system. A. SCHULTZ (COMPUTER SCIENCES CORP.)/S. HEAP (NASA GSFC)/NASA

The accretion theory allows for — even favors — certain local catastrophes. Scientists believe one such catastrophe gave birth to our Moon when a Mars-sized body struck the young Earth.

The concept of accretionary "sweep-up" is now part of a planet's definition, as adopted by the International Astronomical Union in 2006. In the asteroid belt and Kuiper Belt, this process didn't go to completion. Because Ceres and Pluto didn't quite finish the job, both are categorized as dwarf planets.

Observations confirmed the idea of accretionary sweep-up. Microscopic structures of some meteorite classes, which are fragments of unmelted asteroids, show grains of differing compositions stuck together. Beginning in the 1960s, astronomers detected young T Tauri stars with disk-shaped "cocoon nebulae" around them. Spectra of many nebulae revealed silicate dust and ice particles — the very materials from which planets are made. Dusty nebulae around stars like Beta Pictoris show a later stage of the process.

Recent discoveries of planets orbiting a substantial fraction of stars confirm planets are not freaks of nature — they seem to be a natural outcome of the star-formation process. These observations led to wide acceptance of the evolutionary theory of planet formation instead of the theory of planets as a rare accident.

Observations are key

In the 20th century, radioactive isotopes confirmed the Sun and planets formed about 4.5 billion years ago. The method is based on the decay rates of various radioactive substances into "daughter" isotopes. Rock samples from Earth, the Moon, Mars, and meteorites, dated by several different isotopic systems, in different laboratories, in different countries confirmed the solar system's age estimate.

Beyond how and when

Exciting new questions remain for the near future. For example, is our planetary system typical? Most systems discovered differ from ours because they have giant, Jupiter-sized planets close to their parent stars.

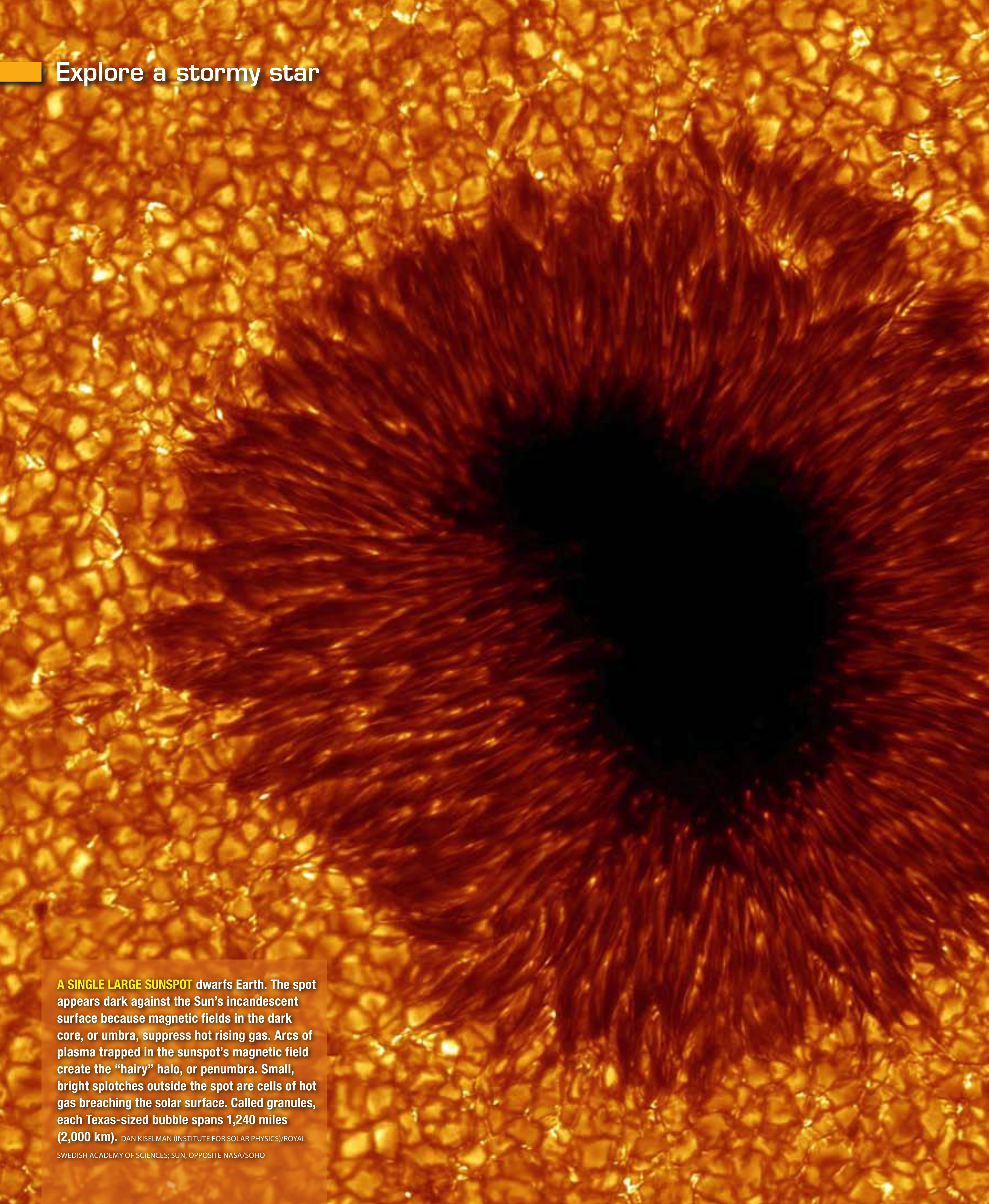
Do most systems experience near-collisions or orbital resonances among their growing giant planets such that at least one giant moves inward, close to its host star? Planet-detecting techniques favor finding giant planets near their stars, so it will take a few more years to get statistics on smaller extrasolar planets and learn how common our solar system is.

Another question involves the final sweep-up of debris as the planets formed. Some researchers see evidence from lunar rocks for a 200-million-year interval of cataclysmic cratering 3.9 billion years ago, which might have affected life's origin on Earth. Calculations suggest resonant effects might have scattered asteroids and caused intense cratering as the planets grew. If such effects happened in other systems, they could have altered their configuration and interfered with life's evolution on other worlds.

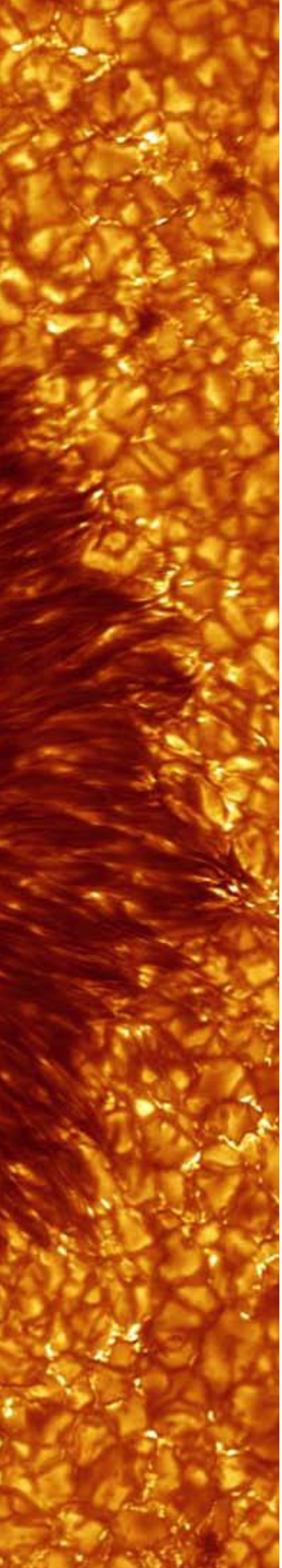
Are habitable worlds common, and if so, are they inhabited? Do alien civilizations, perhaps interstellar in scope, exist? Are cosmic catastrophes, such as supernova explosions or collisions with large asteroids, common enough to interrupt biological evolution and inhibit the growth of planetary civilizations? We don't know.

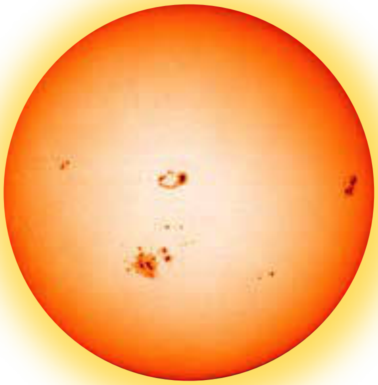
But cosmic history seems to be a combination of gradual evolution punctuated by local catastrophic events. Probing the roles each played in our solar system's birth will yield clues to unlocking the secrets surrounding other stars. ◻

Explore a stormy star



A SINGLE LARGE SUNSPOT dwarfs Earth. The spot appears dark against the Sun's incandescent surface because magnetic fields in the dark core, or umbra, suppress hot rising gas. Arcs of plasma trapped in the sunspot's magnetic field create the "hairy" halo, or penumbra. Small, bright splotches outside the spot are cells of hot gas breaching the solar surface. Called granules, each Texas-sized bubble spans 1,240 miles (2,000 km). DAN KISELMAN (INSTITUTE FOR SOLAR PHYSICS)/ROYAL SWEDISH ACADEMY OF SCIENCES; SUN, OPPOSITE NASA/SOHO





Learning to live with the Sun

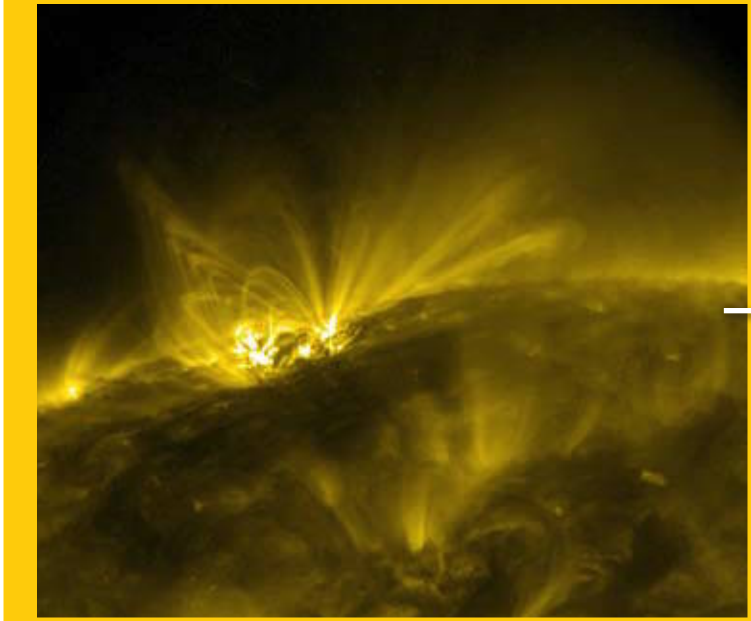
Our star comprises 99 percent of the solar system's material and supplies energy for life on Earth — but it can be a tempestuous neighbor. **by Sten Odenwand**

A single yellow star in a dense star lane of the outer Milky Way would hardly be noticeable among the galaxy's billions. To us, however, it's the most important object in our corner of the universe: the Sun. Astronomers classify the Sun as a G2V "main sequence" star, literally one among billions of similar stars in the Milky Way. It's located 26,000 light years from the galaxy's center, just inside its Perseus arm.

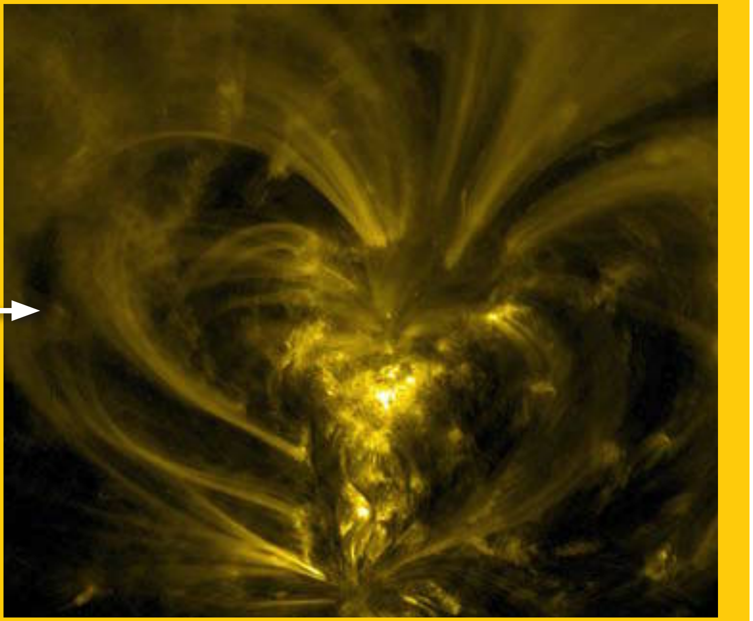
The Sun's imposing volume is just over a million times that of Earth, and it glows incandescent with a surface temperature of 9,900° F (5,500° C). Together, these properties guarantee that, even 93 million miles (150 million km) away, the Sun sheds enough radiant energy to keep our world comfortably warm. The mass of our star, equal to 300,000 Earth's, guarantees it reigns as the solar system's gravitational hub, steering the courses of all objects out to 100 billion miles.

Despite its day-to-day constancy throughout the millennia, the Sun has always made us a little nervous. Will it rise tomorrow? Will it guarantee a bountiful harvest? Today, we're far removed from such primitive concerns, but we also now recognize that our Sun is a fickle neighbor. It's a stormy little star capable of launching nasty "weather" that can impact us in minutes to hours.

Growth of an active region



▲ **AS THE SUN'S ROTATION carried Active Region 10904 into view August 8, 2006, NASA's Transition Region and Coronal Explorer (TRACE) satellite observed it. Loops of million-degree gas arc up into the solar atmosphere.**



▲ **SIX DAYS LATER, on August 14, the region presents itself nearly face-on to TRACE. Thin, well-defined loops show up in perspective to the left and right of the strong central region.** BOTH IMAGES: NASA/TRACE

STATISTICS: Sun

	Sun
Mass	4.384 million trillion trillion pounds
Diameter	864,949 miles
Density	1.41 grams/cc
Weight of 150-lb person	4,194 pounds
Surface temperature	9,950° F
Length of day (equator)	25.4 days
Length of day (45° latitude)	27.3 days

Mass: Total mass (1 million = 10^6; 1 trillion = 10^{12}); **Diameter:** Equatorial diameter; **Density:** Average density in grams per cubic centimeter (water = 1); **Surface temperature:** Effective temperature of photosphere; **Length of day:** Sidereal period.

The key to anticipating these solar tantrums is to understand the Sun's magnetic personality.

Solar magnetism

Magnetism is a painter's brush that adds detail to the Sun's otherwise featureless canvas. Without magnetism, the Sun's face would never change, except for slowly brightening over eons.

As far as astronomers can tell, the Sun's magnetism has been with it since our star was born, 4.6 billion years ago. Like other stars of its kind, the Sun formed from an anonymous interstellar cloud. Over the course of 10 million years, a clump of this gas collapsed under its own weight into a flattened spinning disk. As the gases accumulated, they dragged with them magnetic fields stolen from the primordial cloud.

The Sun, as an infant, was far more active than the sedate adult we've come to know. Back then, the Sun's surface often erupted with violent flares and shot clouds of matter into space. A powerful gaseous outflow called a solar wind blew away the inner solar system's gas and dust. This act revealed the newly formed planets and obliterated their primordial atmospheres.

At first, the Sun's interior Sun was a bubbling cauldron of gases throughout its depth. But once nuclear reactions ignited in its core, this convection zone was pushed outward to occupy a narrow band just below the Sun's surface. It has remained there ever since.

Within the convection zone's roiling maelstrom, the Sun creates new magnetic fields as it destroys older ones. The solar magnetic field waxes and wanes over an 11-year activity cycle first discovered in 1843 by German astronomer Heinrich Schwabe. At its peak, sunspots dot the surface in bewildering and ominous numbers. At its ebb, the surface appears seemingly tranquil and unblemished. It's the constant cycling between these extremes that stirs up so much trouble for us.

Why cycles?

Scientists think the Sun's activity cycle goes something like this. Heated gases in the convection zone rotate around the Sun faster near the equator (once in 25 days) and slower near the poles (about 36 days). At a depth of about 124,000 miles (200,000 km), near the base of the convection zone, things work quite differently. There, the Sun rotates at the same pace from pole to equator, much as our solid Earth spins on its axis. As a result, large speed changes occur in a zone called the tachocline. This is where solar scientists believe the Sun generates its magnetic field.

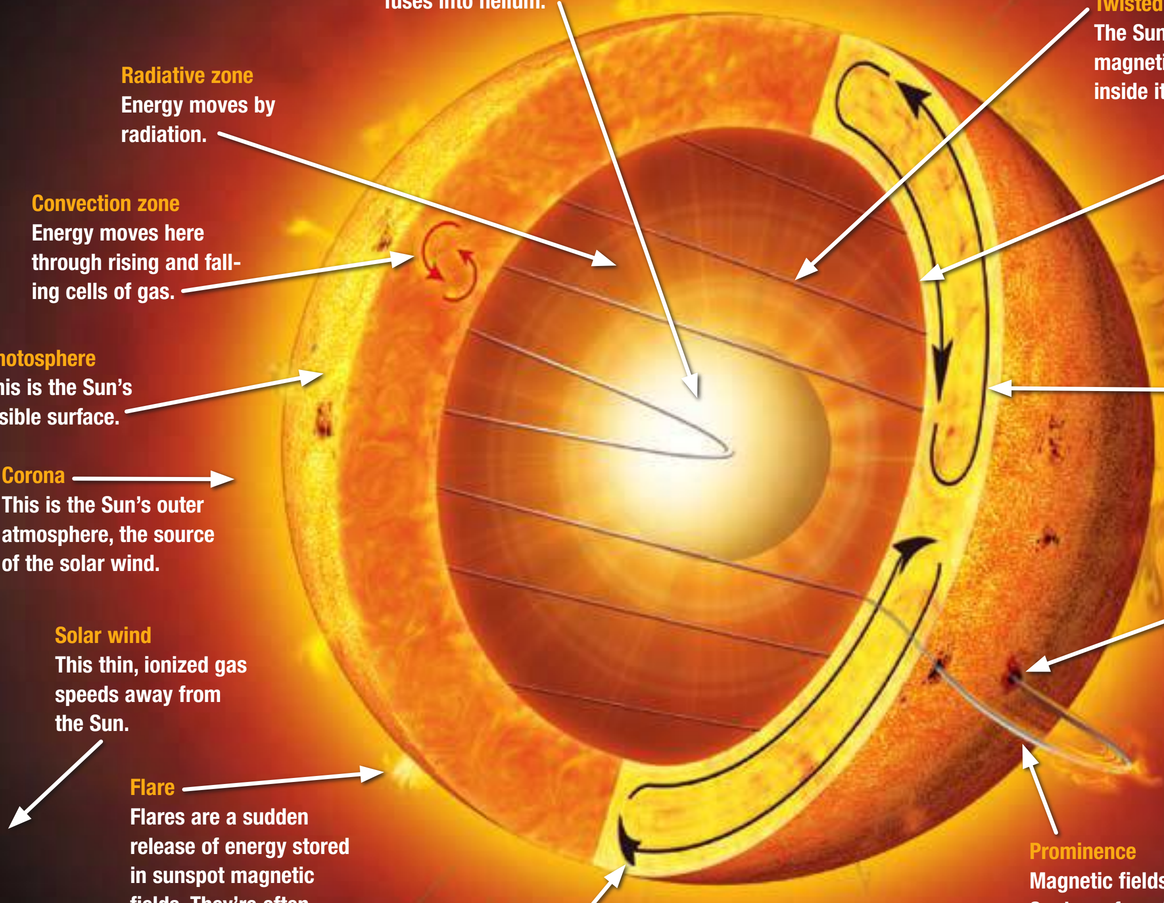
Within the tachocline, magnetic fields are generated, amplified, and stretched into vast million-mile tubes of energy. Initially, these magnetic tubes extend north and south along lines of solar longitude. But as the Sun spins, the tubes stretch east to west. With each solar rotation, the tubes wrap more tightly.

This concentrated magnetic energy makes the tubes buoyant, so they rise to the solar surface. When a tube breaches the surface as a horseshoe-shaped loop, each end of the loop becomes one of a pair of sunspots with its own polarity: north or south. The magnetic tube fans out like a clam opening its shell into a beautiful arcade. These arching magnetic loops appear prominently in views from solar-monitoring satellites such as NASA's Transition Region and Coronal Explorer (TRACE) and Ramaty High Energy Solar Spectroscopic Imager (RHESSI).

Sten Odenwald *is a professor of astronomy at Catholic University in Washington.*

Inside the Sun

THE SUN'S BASIC FEATURES, both inside and out, are illustrated here. Energy produced in the Sun's core through the fusion of hydrogen into helium ultimately powers these phenomena. *ASTRONOMY:* ROEN KELLY



Coronal mass ejection (CME)
These billion-ton clouds of charged particles erupt frequently from the Sun. They move at millions of miles per hour.

Core
This is the Sun's energy source, where hydrogen fuses into helium.

Magnetic field
The Sun's global magnetic field is 10 times stronger than Earth's. Field lines exit the Sun at the positive pole and enter at the negative pole.

Twisted field lines
The Sun's rotation twists magnetic field lines deep inside it.

Radiative zone
Energy moves by radiation.

Convection zone
Energy moves here through rising and falling cells of gas.

Photosphere
This is the Sun's visible surface.

Corona
This is the Sun's outer atmosphere, the source of the solar wind.

Solar wind
This thin, ionized gas speeds away from the Sun.

Flare
Flares are a sudden release of energy stored in sunspot magnetic fields. They're often associated with CMEs.

Tachocline
The Sun spins like a fluid above this layer, and like a solid body below it. The intense shear here helps create the global field.

Meridional flow
This "conveyor belt" moves leftover fields poleward and deep into the Sun.

Sunspots
Dark spots mark where magnetic fields, amplified inside the Sun, break through the surface.

Prominence
Magnetic fields suspend gas far above the Sun's surface. Prominences sometimes erupt.

Sunspot leftovers
Fading sunspots leave behind weak magnetic fields opposite to the Sun's global polarity. They accumulate at both poles and help reverse the global field. This starts a new solar activity cycle.

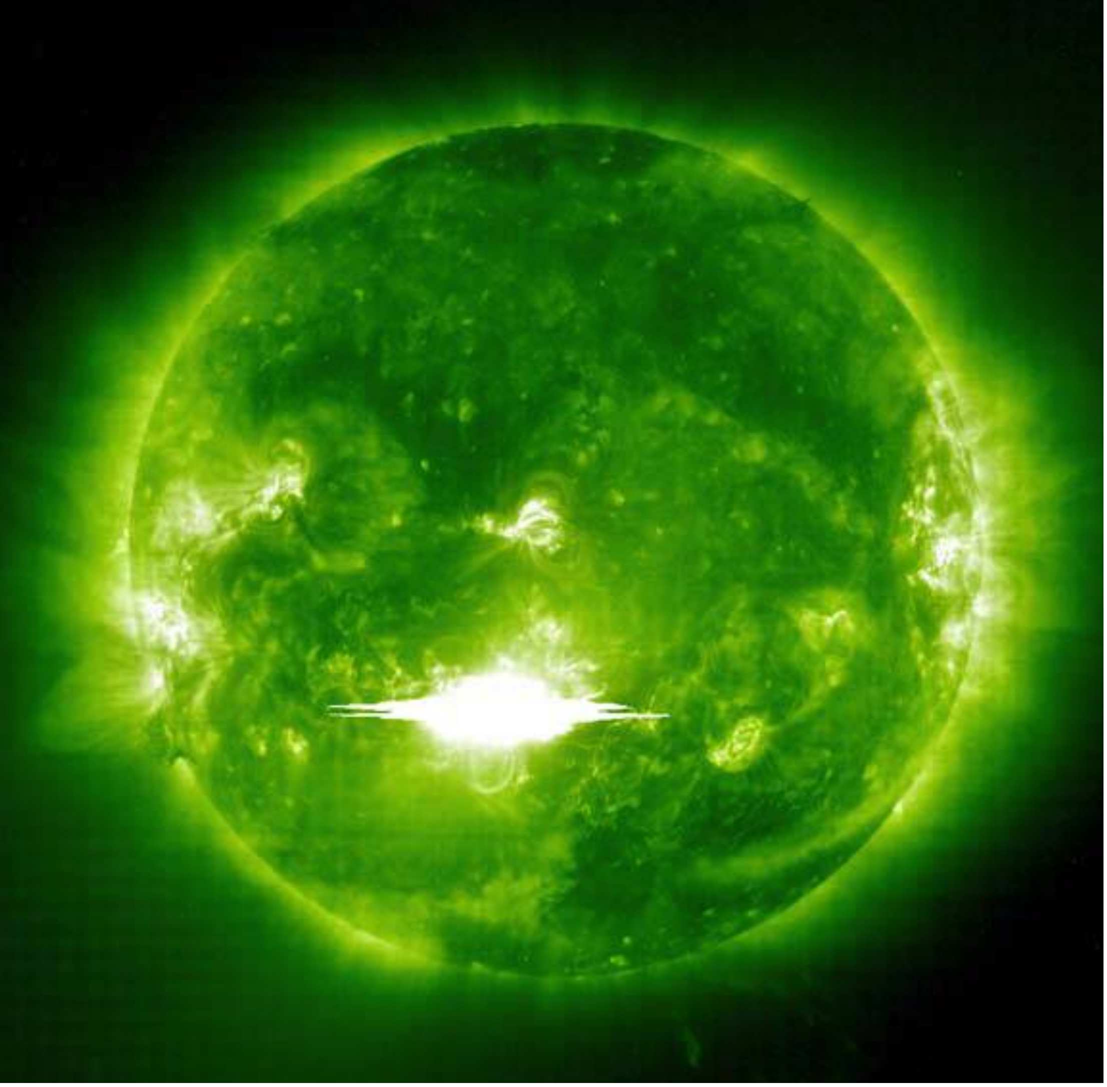
Over time, sunspot fields break apart and diffuse across the surface. They flow poleward at about a mile an hour and then gather into larger magnetic collections. From start to finish, it takes about 11 years for all of the sunspot energy to be released. The Sun flips from its original magnetic polarity to the opposite one, and then the whole process begins anew.

This explanation for the Sun's behavior, first put forward by astronomer Eugene Parker in the 1950s, now forms the backbone of modern solar physics. The Sun won't return to its original polarity for another 11 years. Solar physicists refer to the period from one magnetic orientation to another as the 22-year Hale cycle.

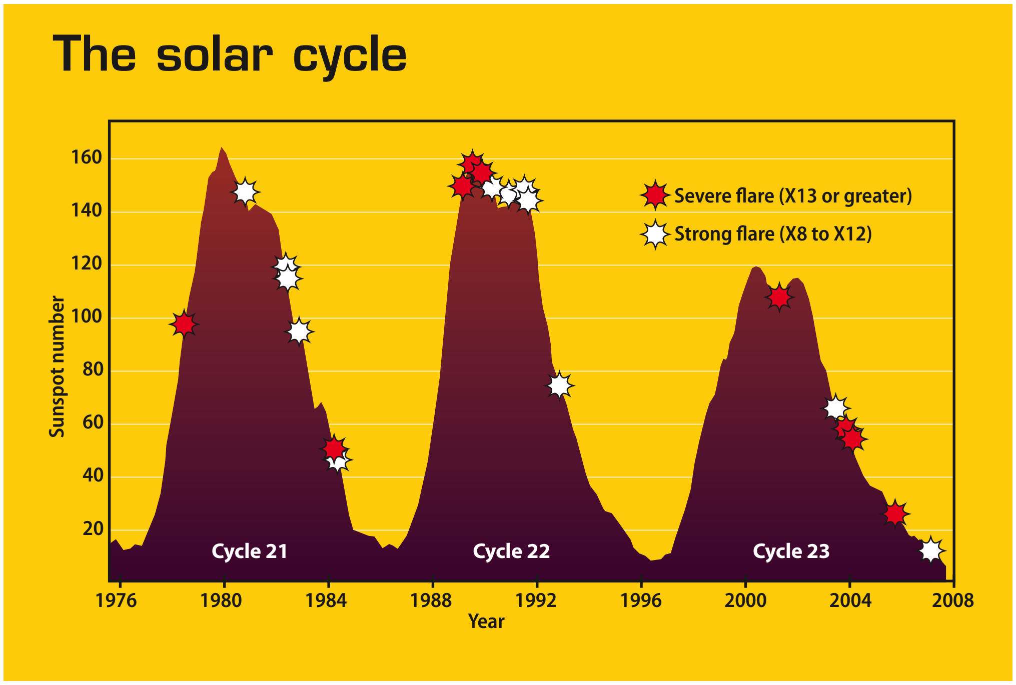
Since Parker's breakthrough, supercomputer models have become so good they now can simulate sunspot cycles in detail. Astronomer Mausumi Dikpati and her colleagues at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, recently predicted the strengths and timings for the next three solar cycles.

According to her research, the cycle starting up in 2008, called Cycle 24, may be much more intense than Cycle 23, which just ended.

▲ **THE PEARLY CORONA,** the Sun's outermost atmosphere, appears during a total solar eclipse. Portions of the corona stream away from the Sun to form the solar wind, an outflow that encompasses the entire solar system. FRANCIS REDDY

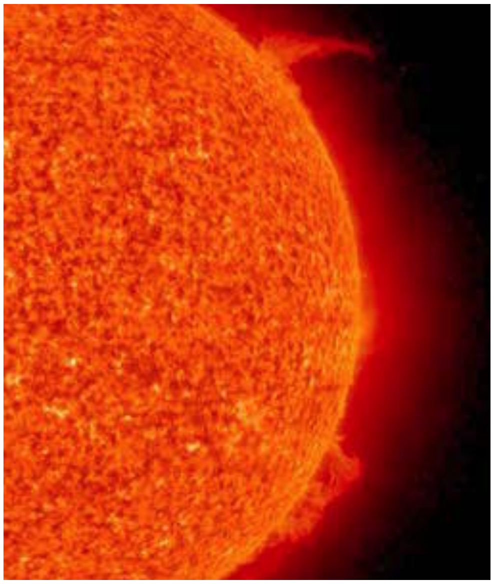


▲ **THE SOLAR AND HELIOSPHERIC OBSERVATORY SATELLITE caught one of the largest solar flares on record October 28, 2003. The X17-class outburst appears overexposed in this image.** NASA/ESA/SOHO



The solar cycle

▲ **THE LAST 30 YEARS have seen three sunspot cycles. This chart plots the mean number of sunspots (vertical axis) by year. Colored circles show when strong (white) and severe (red) solar flares erupted. As sunspots increase, so does the number of flares. But the Sun's most intense explosive events tend to occur on the cycle's down side.** *ASTRONOMY*: ROEN KELLY, AFTER FRANCIS REDDY



▲ **SOLAR PROMINENCES twist and stretch above the Sun's limb in this extreme ultraviolet image from August 2007. Prominences are clouds of cooler gases controlled by powerful magnetic forces that extend into the Sun's corona.** NASA/STEREO

The solar menagerie

Solar magnetism creates many different phenomena that astronomers can view throughout the solar cycle.

Sunspots. In a sunspot's dark center, or umbra, magnetic fields are concentrated 1,000 times. Electrically charged particles act like beads on a string — they can't easily cross magnetic field lines. The convection of hot, churning gases directly below the spot all but ceases. The magnetically trapped gases cool nearly 3,600° F (2,000° C) below the Sun's surface temperature and produce little light, thereby making the spot appear dark.

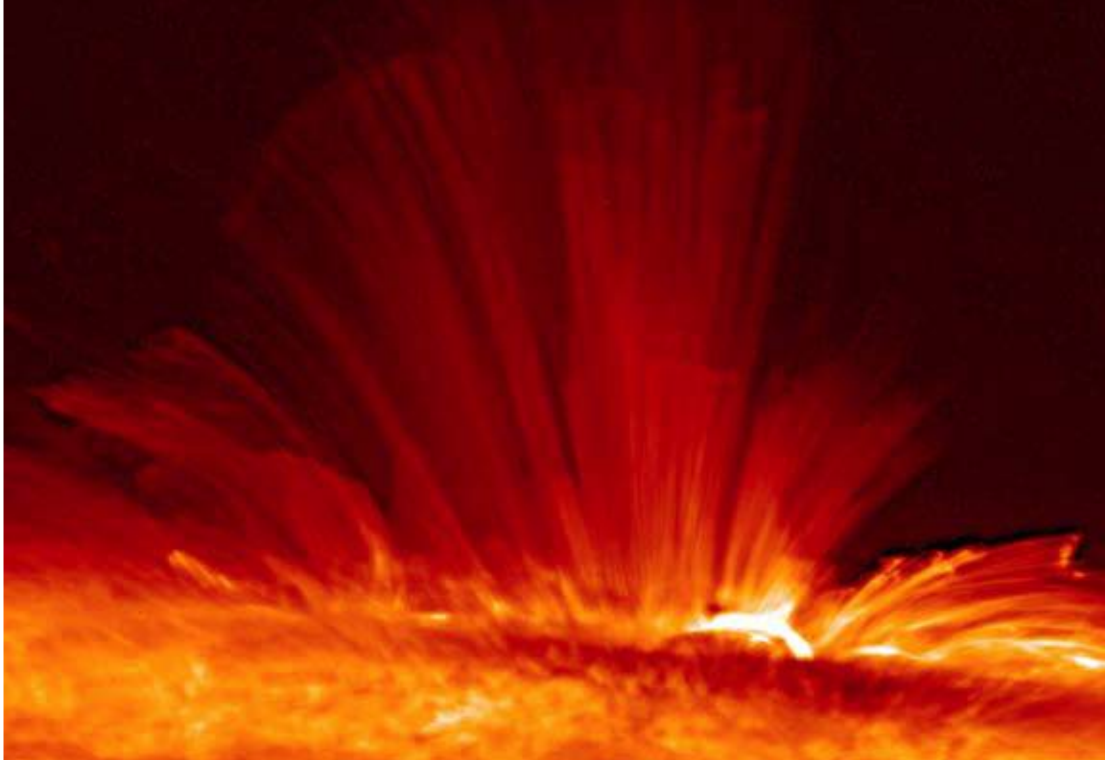
A sunspot's dark center is surrounded by a brighter zone called the penumbra. When seen close-up, the penumbra resolves itself into innumerable dark plasma filaments. They show where hot gas flows along the magnetic lines at thousands of miles per hour.

Prominences. Graceful, complex, magnetic loops arch above sunspots and reach well into the Sun's corona. Occasionally, trapped plasma fills a few of these otherwise invisible loops. The gases emit their own light, revealing detailed magnetic patterns. Some prominences remain stable for many weeks or months, but nothing lasts forever. As sunspots move and merge, the delicately balanced magnetic arcades become unstable. Within a few hours, the trapped plasma either launches into space or rains down onto the solar surface.

Flares. When sunspot magnetic fields become badly twisted or tangled, invisible magnetic stresses build up. Sometimes, sudden rearrangements called reconnections relieve these stresses. In a reconnection, a complex magnetic field relaxes into a simpler shape, like a rubber band pulled to the breaking point. This change releases a vast amount of energy, equivalent to thousands of hydrogen bombs detonating at once, and results in X-ray emission from million-degree heated gases. During the last sunspot cycle, satellites detected more than 20,000 X-ray flares. The 100 most powerful of these, dubbed "X-class," can cause hour-long shortwave radio blackouts across Earth's entire sunlit hemisphere

Coronal mass ejections (CMEs). A more gradual phenomenon also involves changing magnetic fields. But instead of intense bursts of electromagnetic energy, these explosions launch billions of tons of plasma into space at up to 4 million mph (7 million km/h). Spacecraft can track these CMEs throughout the inner solar system. When CMEs reach Earth, trapped particles within Earth's magnetic field gain energy and flow into the polar regions, where they cause spectacular aurorae.

Solar wind. A dilute expanding gas flows out from the solar corona into interplanetary space. Its density is so low, only a few particles could be found in a sugar-cube-sized volume. The solar wind travels at 895,000 mph (1.4 million km/h) and flows throughout the planetary system. The solar wind sprays from the Sun in arcs, like water from a garden sprinkler. This pinwheel of plasma contains sectors with magnetic fields of opposite orientation. High-speed gas streams plow through the solar wind, too.



▲ **THE JAPANESE SOLAR OBSERVATORY Hinode imaged this arcade of magnetic loops November 20, 2006. The loops, which fan out above a sunspot, form as ionized gas responds to local magnetic conditions.** JAXA/NASA

What's next?

In mid-2008, the Sun will reach sunspot minimum. The new cycle, the 24th since official counting began in 1760, then will commence. Sunspots will steadily grow in number, peaking at sunspot maximum around 2011. Some models forecast that Cycle 24 will resemble the two more active cycles that preceded Cycle 23.

The current disagreement regarding model forecasts for Cycle 24 is more than academic. If the cycle achieves the high peak performance some researchers expect, it's mostly bad news for satellite owners, the electrical power grid, and even civilian aviation. It means a greater threat of disruption for many key services we rely on and a significantly greater likelihood of blackouts and satellite malfunctions than we experience now, as Cycle 23 wanes.

SEVEN LITTLE-KNOWN SUN FACTS

1. The first unambiguous report of solar prominences appears in the Russian *Chronicle of Novgorod.* Observers reported "live embers" extending from the Sun during the May 1, 1185, total solar eclipse.
2. Sunspots can be so cold, water vapor — steam — forms within them. In 1995, astronomers detected steam in the cool umbral regions of some sunspots.
3. The spectacular solar flare of November 4, 2003, was so powerful, the total energy reaching Earth could have met global needs for more than 1,000 years.
4. A CME that arrived March 13, 1989, caused a massive electrical blackout in Quebec that affected more than 5 million people. NASA spacecraft now give up to 3 days warning by detecting CMEs as they approach Earth.
5. At its core, the Sun's 25 million degrees Fahrenheit (13.6 million degrees Celsius) plasma has a density about 10 times greater than lead. At the Sun's roiling surface, the density falls to that of our own atmosphere — at the top of Mount Everest.
6. Light takes up to 20,000 years to work its way from the Sun's core to the surface. Once it gets there, light takes about 8 minutes to reach Earth.
7. Each second, the Sun's core converts 4 million tons of matter into light.

Curtain call

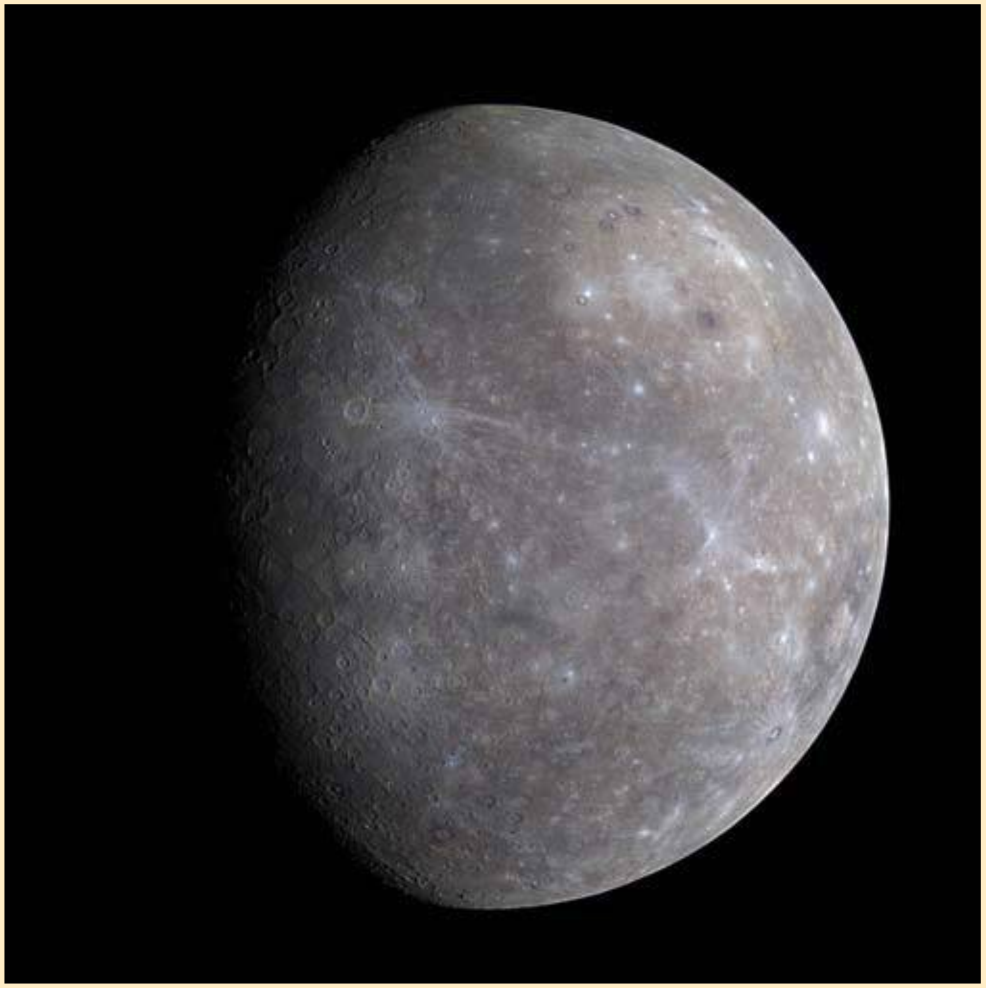
Even if we could outlive the Sun's temper tantrums, the story would get only worse. After a long adulthood, the relentless pace of stellar evolution will continue to drive the Sun's brilliance steadily higher and place the entire terrestrial biosphere under increasing stress.

The Sun's luminosity has grown by 1 percent every 100 million years. Since its birth, the Sun has brightened by more than 30 percent. This extra warmth helped make early Earth an abode for life. But the Sun's continued brightening will eventually extinguish life on this planet.

Models developed by astronomers Peter Ward and Donald Brownlee at the University of Washington predict Earth will continue to warm in synchrony with the Sun. Half a billion years from now, with a Sun only 5-percent brighter than it is today, we will reach a tipping point. Greenhouse gases, such as water vapor evaporating from the surfaces of heated oceans, will magnify solar heating and drive year-round terrestrial temperatures above 110° F (43° C) from pole to pole.

The era of multicellular life began on Earth 600 million years ago. Inevitably, 600 million years from now, only bacteria will survive.

The exact details of the far future may be murky, but perhaps the ancients had it right all along. Our Sun is, at its core, an unreliable neighbor. Monitoring its changes and knowing its temperament allow us to exist in a semblance of safety and comfort. Ignoring its penchant for occasional violence fills us with a false sense of safety and sets us up for unpleasant surprises.



MESSENGER SPIED MERCURY with its Wide Angle Camera (WAC) January 14, 2008. This visible-infrared color composite combines images taken through three of the WAC's 11 filters. MESSENGER was about 80 minutes from its closest pass of Mercury — 17,000 miles (27,000 km) — when it acquired this image.

ALL IMAGES: NASA/JHUAPL/CARNEGIE INSTITUTION OF WASHINGTON

Seeing **Mercury** in a whole new light

In early 2008, NASA's MESSENGER spacecraft gave astronomers a close-up view of Mercury.

by Clark R. Chapman

The planet Mercury is a challenge to study, even though it is closer to Earth than Mars. Darting quickly around the Sun, this small, metal-rich, rocky world can be glimpsed only occasionally just after sunset or right before sunrise.

Just as it's hard to see objects when we face into a spotlight, Mercury's proximity to the Sun stymies optical telescopes. The Sun's intense heat also hinders spacecraft investigation of Mercury. The energy required to match Mercury's swift velocity and place a vehicle into orbit around the planet is problematic.

Until 2008, only one spacecraft had studied Mercury. Mariner 10, which flew past the planet three times in 1974–1975, saw only one side of Mercury. A new epoch of intensive study began January 14, 2008, when NASA's MESSENGER spacecraft executed the first Mercury flyby since Mariner 10, some 33 years ago.

MESSENGER is an acronym for MErcury Surface, Space ENvironment, GEochemistry, and Ranging, a phrase that attempts to capture the mission's range of scientific goals and approaches to exploration. Johns Hopkins University's Applied Physics Laboratory developed the mission. Launched August 3, 2004, MESSENGER carries eight state-of-the-art instruments, several of which have multiple modes for exploring Mercury's surface, interior, and space environment.

Mariner 10 discovered Mercury's small magnetosphere, which is buffeted by the Sun such that the planet's surface is sometimes exposed to the solar wind. Despite a superficially lunar-like landscape, Mercury exhibits several unique terrains. With no instrument capable of assessing mineral or chemical composition, Mariner 10 made little progress in helping astronomers understand why Mercury has such a large core. The planet's core accounts for more than 40 percent of its mass, as contrasted with 16 percent for Earth's core.

During the decades since Mariner 10's visit, scientists have made only incremental advances studying Mercury. They have identified some gases in its slight atmosphere. The giant Arecibo radar dish has shown large topographic features on Mercury's previously unseen side. In 1991, the Very Large Array in Socorro, New Mexico, detected surprisingly strong echoes of radio signals transmitted by the Jet Propulsion Laboratory's Goldstone radar bouncing off Mercury's poles. Apparently, water ice lies within permanently shadowed polar-latitude craters. Previously, scientists thought water ice could not exist on this broiling planet.

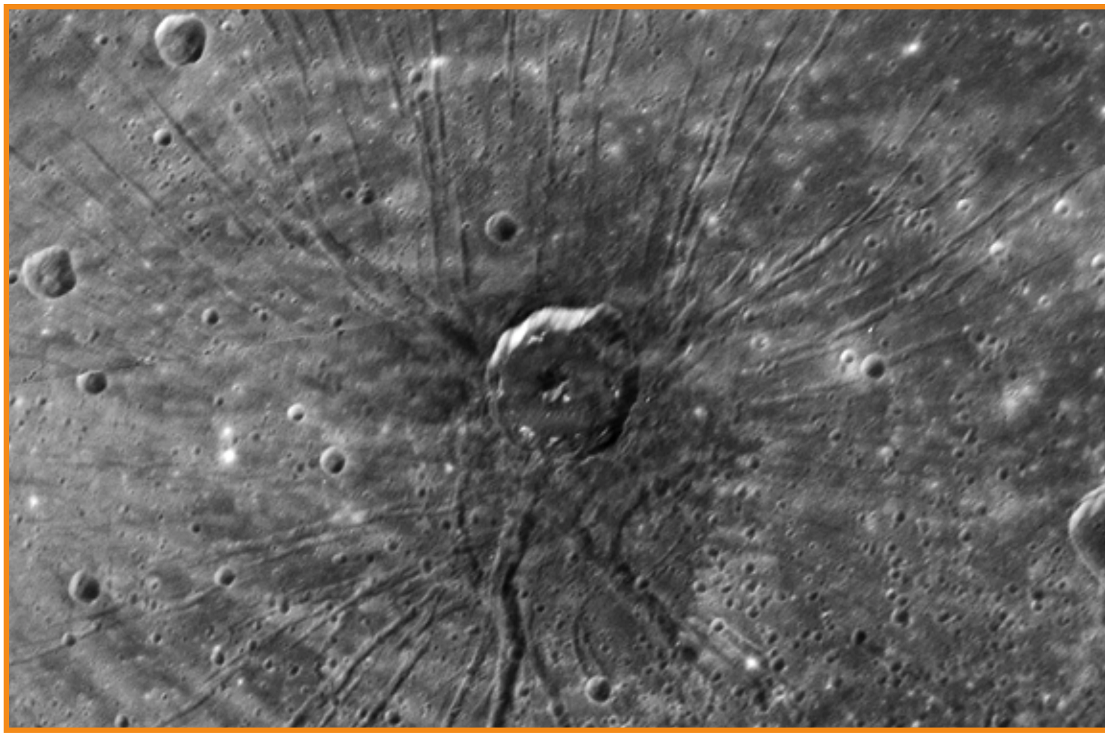
In May 2007, clever use of the Goldstone and Arecibo radars and the Green Bank radio telescope precisely established the orientation of Mercury's rotation. The measurements prove the outer parts of Mercury's enormous core are at least partially molten. This allows the planet's mantle and crust to slip more due to solar tides than would be possible for a rigid planet.

Mysteries still abound

Despite these advances, Mercury still hides more mysteries than any other planet. But the veil began to lift when MESSENGER made the first of its scheduled three flybys before it settles into orbit around the planet in 2011. To accomplish orbital insertion, the main engine will have to reduce the spacecraft's velocity by nearly 2,200 mph (3,600 km/h).

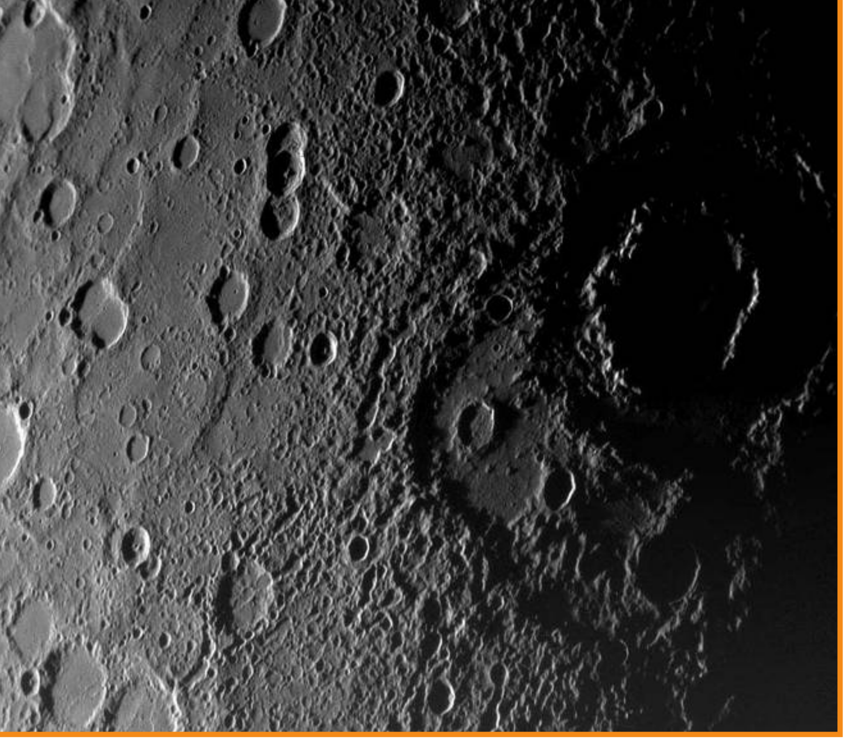
Exploration of Mercury and its magnetosphere from MESSENGER's planned elongated orbit should finally reveal Mercury's traits as thoroughly as we know our own Moon. The spacecraft's orbit will extend from about 125 miles (200 km) at its closest, to about 9,300 miles (15,000 km) at its farthest. MESSENGER will make one circuit every 12 hours.

One of the puzzles MESSENGER will try to resolve, once it enters into Mercury orbit, is how ice can survive near the innermost planet's poles. The Moon is a much cooler world that also has permanently shadowed craters, but it lacks the abundant polar ice Mercury seems to possess. MESSENGER's task will not be easy because the very shadows that may help to preserve the ice will prevent those regions from

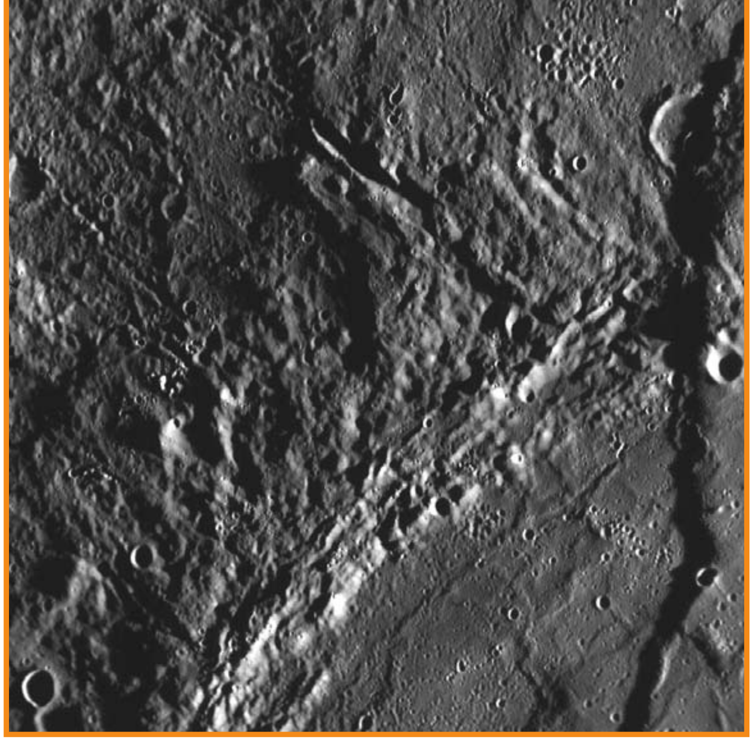


▲ **THE SPIDER,** a feature named by MESSENGER's science team, lies near the center of Mercury's Caloris Basin. Radial troughs, unlike anything seen by the Mariner 10 spacecraft, inspired the name. Scientists think these troughs show the breaking apart of materials on the basin's floor.

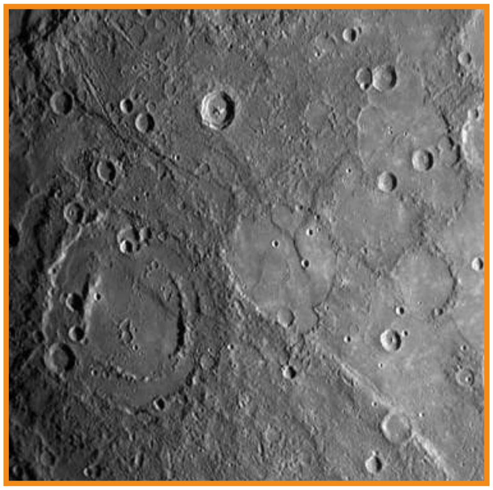
Clark R. Chapman *is a senior scientist with the Southwest Research Institute in Boulder, Colorado.*



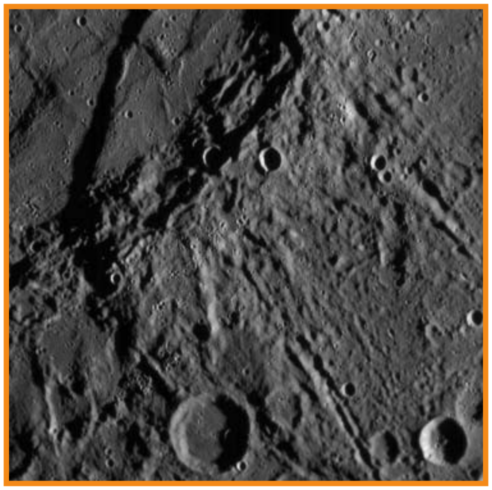
▲ **VIVALDI CRATER**, named after the Italian composer, appears shadow-filled and double-ringed in this MESSENGER Narrow Angle Camera image. The crater's outer ring is about 125 miles (200 km) across. Scientists can identify craters as small as 0.6 mile (1 km) in this image.



▲ **A LARGE SCARP,** which shows a part of Mercury never seen close-up before, crosses vertically through this image (far right). Astronomers believe giant scarps formed when Mercury's interior cooled and the entire planet shrank as a result. Smaller scarps result when part of the surface overrides another.



▲ **THIS DOUBLE-RINGED CRATER** (lower left) appears to be filled with smooth plains material that may be volcanic. After the crater formed, the prominent scarp (running from upper-left to lower-right) disrupted the crater's shape along its northern (top) edge. This MESSENGER image also shows the scarp cut the small crater at lower right.



▲ **GREAT FORCES IN MERCURY'S CRUST** sometime in the past have thrust the terrain in the right two-thirds of this image up and over the flatter terrain to the left. An impact crater subsequently has destroyed a small part of the scarp near the bottom. This region of Mercury lies near the planet's equator and measures about 100 miles (161 km) across.

being readily seen. However, MESSENGER has other ways to discover whether the deposits are made of ice or even sulfur, as some scientists suggest.

Other issues involve Mercury's origin and its geological history. Many Mariner 10 observations seem contradictory. That 1970s mission discovered the planet's bipolar magnetic field, which suggests a molten core. Yet, such a small planet should have long since cooled. And Mariner's images of craters and other features (including numerous curving cliff faces, or scarps) suggest the planet has been geologically stagnant for as long as the Moon, or even longer — perhaps for nearly 4 billion years.

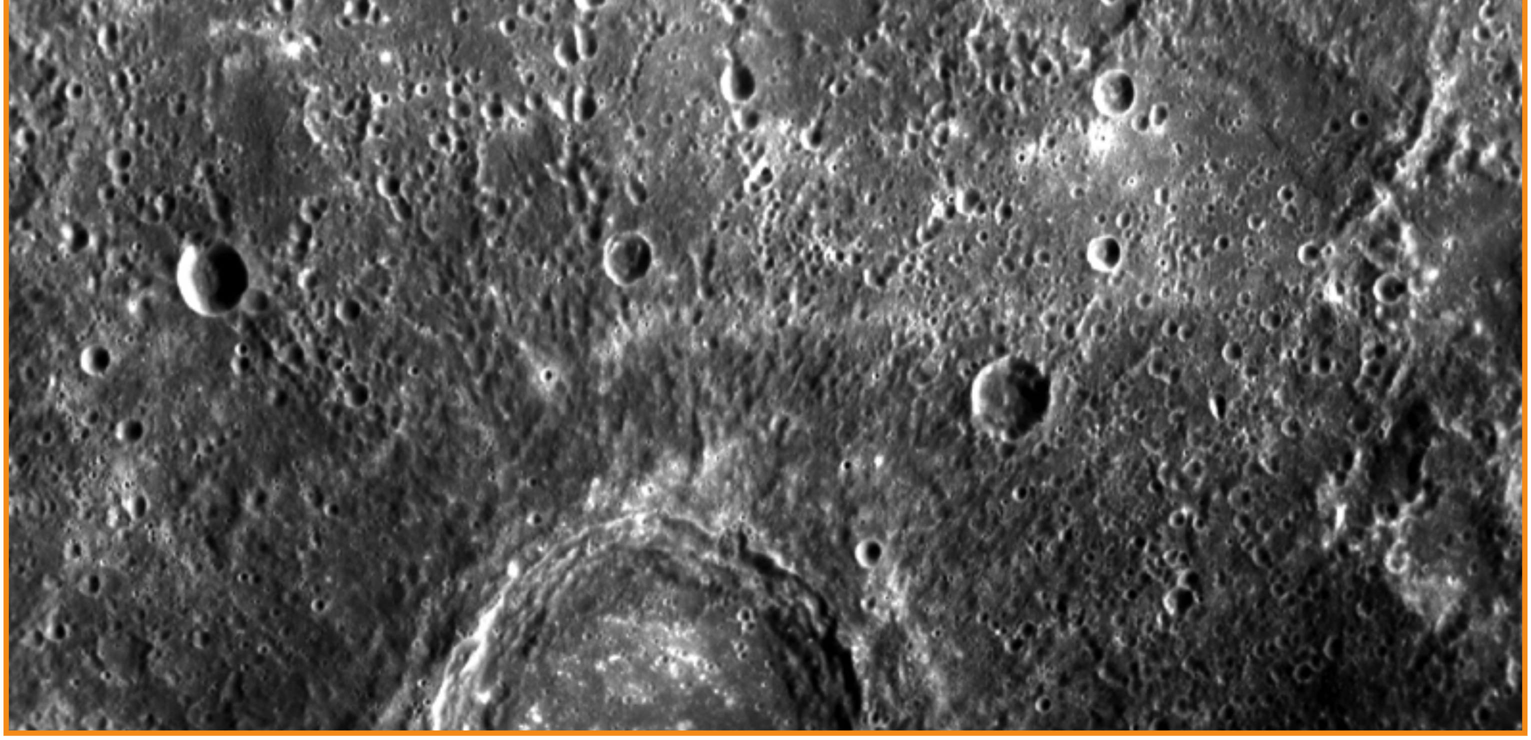
The so-called Late Heavy Bombardment, as recorded by Apollo rocks on the Moon, ended about 3.85 billion years ago. The associated bombardment of Mercury, astronomers think, created the great Caloris Basin, and most cratering may have ended then, too. Mariner 10 data indicate Mercury may lack the Moon's lava plains, called maria, that record continuing lunar volcanism for nearly another billion years. That view is changing, however, following MESSENGER's first close-up pictures of the side of Mercury never seen by Mariner 10. The new images show volcano-like structures.

Apparently, the outer parts of Mercury's enormous metallic core remain molten. One possible reason is that Mercury, or at least much of its material, didn't form near its innermost position in the family of planets, but somehow moved there after forming much farther away from the Sun.

Volatile compounds like sulfur, which should never have existed so close to the Sun, are abundant in the more distant asteroids. Sulfur could lower the melting point of the metal in Mercury's core so it could remain molten at a lower temperature. If the core is molten, it may generate Mercury's magnetic field through dynamo action, similar to an electric generator.

A vital puzzle concerns the apparently ancient "death" of Mercury's surface geology. Perhaps the contraction of Mercury's crust, evidenced by the great sinuous cliffs and caused by the planet's cooling, choked off pathways for internal magma to reach the planet's surface.

So, surface geological processes may have ended early, except for occasional asteroid and comet impacts. Alternatively, active geological processes could have continued much longer.



THIS MOSAIC taken by MESSENGER's Narrow Angle Camera shows an area about 230 miles (370 km) across and reveals features as small as 0.25 miles (400m) wide. The image shows part of a large, fresh crater with secondary crater chains. Such features formed when debris blasted out of the main crater by a meteorite fell back to the surface. These chains, in addition to the rest of the ejecta, create the complicated, hilly terrain surrounding the primary crater.

This could be true if many of the seemingly ancient craters on Mercury actually formed more recently. It is possible that an as-yet-unseen population of asteroids interior to Mercury's orbit, called vulcanoids, remained to pummel Mercury long past the Late Heavy Bombardment. Any remaining vulcanoids would be difficult to find from Earth because of their proximity to the Sun. MESSENGER's cameras may yet find some vulcanoids, which could unravel some of the conundrums surrounding Mercury's planetary evolution.

New revelations

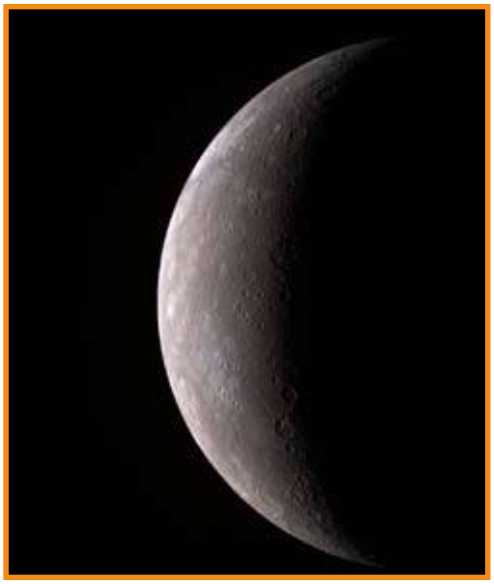
MESSENGER's January 2008 flyby produced images of plentiful scarps, implying even greater compression of Mercury's crust. The probe saw numerous giant impact craters and basins, as well as an abundance of secondary craters, made when fragments and other material ejected by the impact explosions re-impacted Mercury's surface.

Astronomers have now seen the full breadth of the Caloris Basin. It is about 960 miles (1,550 km) across, larger than the 800 miles (1,300 km) scientists had previously estimated from the basin's eastern portions viewed by Mariner 10. An intricate set of both radial and concentric faults cracked Caloris' floor. These patterns are unlike any seen elsewhere on Mercury or the Moon. Scientists are now seeing, in the first pictures and infrared spectra, better evidence for volcanism than Mariner 10 revealed. Still another large section of Mercury not seen yet will come into view during MESSENGER's second flyby, in October 2008.

STATISTICS: Mercury vs. Earth

	Mercury	Earth comparison
Mass	0.7280 trillion trillion pounds	5.5% of Earth's
Diameter	3,032 miles	38.3% of Earth's
Density	5.43 grams/cc	98.4% of Earth's
Weight of 150-lb person	57 pounds	37.8% of Earth's
Distance from Sun	35.98 million miles	38.7% of Earth's
Orbital period	87.969 days	24.1% of Earth's
Length of day	4,223 hours	176 times Earth's

Mass: 1 trillion = 10^{12}; **Diameter:** Equatorial diameter; **Density:** Average density in grams per cubic centimeter (water = 1); **Distance from Sun:** Average distance; **Orbital period:** Sidereal period; **Length of day:** Average time between successive noons; **Earth comparison:** Ratio of Mercury's to Earth's value.



AS IT PASSED MERCURY, MESSENGER observed about half the hemisphere missed by Mariner 10, which flew by the planet in 1975. Like the previously mapped part of Mercury, this hemisphere appears heavily cratered. Astronomers now see the entire Caloris Basin (upper right), which formed by the impact of a large asteroid or comet. This image showed (for the first time) several other multi-ringed basins and dark, smooth plains.

Future exploration

Whatever secrets remain after the current mission may be revisited in 2019, when the European/Japanese BepiColombo probe enters orbit around Mercury. This mission, planned for launch in 2013, is named after Giuseppe "Bepi" Colombo, an Italian physicist who in 1965 explained why Mercury rotates with a day that is two-thirds as long as its 88-day orbital period around the Sun. Colombo's explanation came shortly after early planetary radar observations overturned the notion that Mercury kept one face toward the Sun, like the Moon does toward Earth. The long-standing error resulted from the hide-and-seek game Mercury plays as it swings around the Sun.

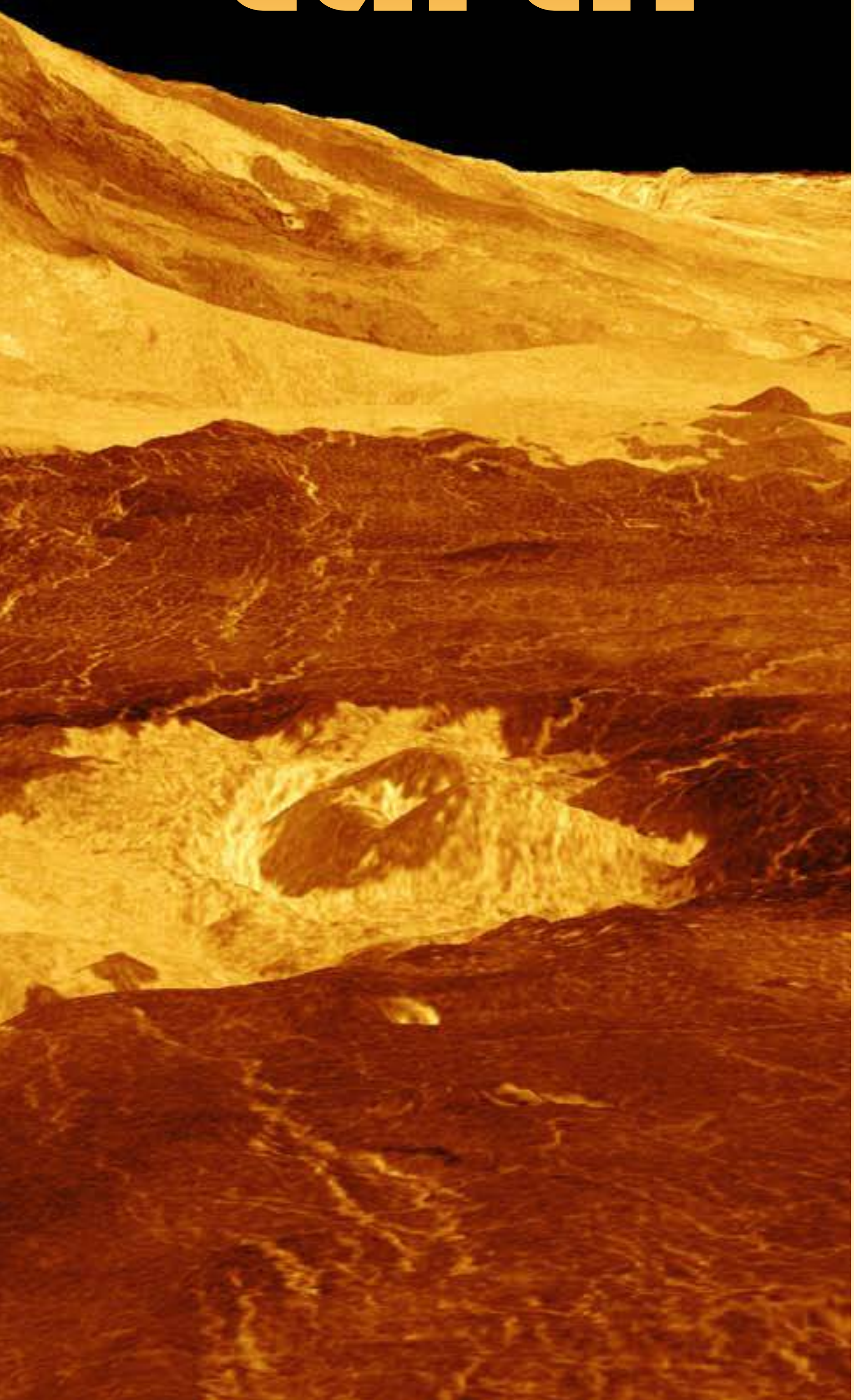
Despite Mercury's elusive ways, we have begun to learn much more about the innermost and smallest (and second-hottest) planet in the solar system. ◻

An Earth gone wrong?

How Venus sheds light

MAAT MONS RISES majestically above Venus' volcanic plains. In this perspective view of this 5-mile-high (8 km) volcano, created from Magellan radar images and altimetry, lava flows extend hundreds of miles. The vertical scale has been exaggerated 10 times. NASA/JPL/USGS

on Earth



Volcanos turned Venus inside out hundreds of millions of years ago. What does this tell scientists about Earth's tortured history?

by James W. Head III

Venus, Earth's radiant morning and evening "star," has long engaged our attention. It stands out as the brightest object in the sky besides the Sun and Moon. And unlike the seemingly fixed background stars, it was one of a handful of cosmic "wanderers" that attracted the Babylonians' attention over 5,000 years ago. More than 2,000 years ago, Mayans personified Venus as the god of rain and built observatories to track the planet's path through the skies to predict when wet seasons would occur.

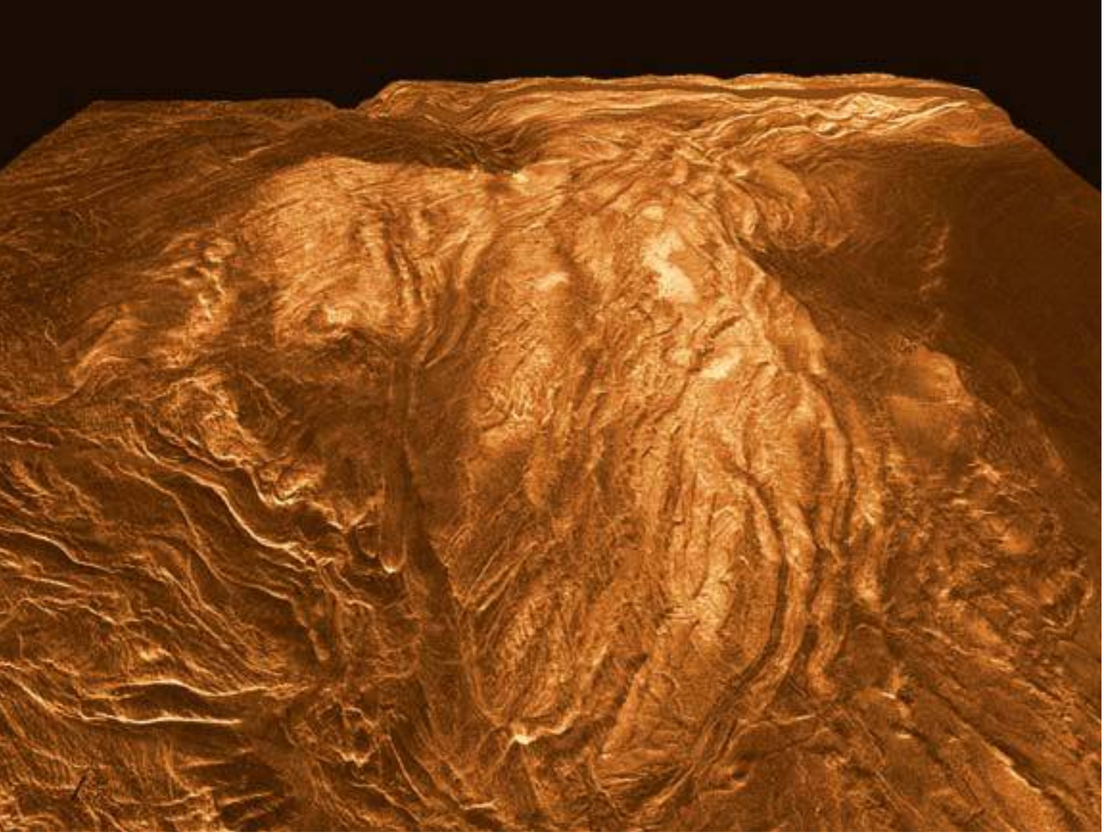
With the transition from myths to scientific observations, we began to understand Venus' significance. Galileo discovered the planet has phases in 1610, and Russian astronomer Mikhail Lomonosov correctly inferred the presence of an atmosphere during Venus' transit of the Sun in 1761. Learning that Venus and Earth have nearly identical diameters led to the conclusion that it might be Earth's twin. Brightness measurements and assumptions of earthlike water abundance buttressed that concept.

The inability to see Venus' surface fueled human imagination. Some people envisioned steamy swamps, creating an entire genre of art, science-fiction literature, and movies. All this was brought to a close about 20 years before the beginning of the Space Age, when astronomers concluded Venus' atmosphere consists predominantly of carbon dioxide, and that the surface temperature and pressure are much higher than those on Earth.

This began a retreat from the concept of Venus as Earth's twin. Yet it also led to a series of discoveries that were no less important in our fundamental understanding of Earth. Astronomers learned Venus' rotation is slow and retrograde (opposite that of the other planets); the clouds consist of sulfuric acid, not water; and the surface temperature is hot enough to melt lead. Botticelli's beautiful Venus was transforming into Dante's searing Hell.

These findings posed totally new questions: If Earth and Venus weren't identical twins, were they fraternal twins, or perhaps siblings? Or were Earth and Venus from an entirely different family altogether?

James W. Head III *is a professor in the Department of Geological Sciences at Brown University in Providence, Rhode Island.*



▲ **FOLDED MOUNTAIN BELTS,** **like Freyja Montes seen here, lie at the edges of continent-like plateaus. Although such mountain belts signify plate tectonics on Earth, scientists found no smoking gun for such episodes on Venus.** NASA/JPL

A fresh look

With the 1957 launch of Sputnik and the advent of the Space Age, answers to some of these mysteries were at hand. Yet space probes raised other, even more intriguing questions. A parallel revolution in our understanding of Earth showed its surface to be mobile on geological time scales. Geoscientists learned that sea-floor spreading and continental drift could be combined into a theory of global plate tectonics. Earth's outer, rigid layer, the lithosphere, comprises a series of plates. They are created at mid-ocean ridges, move laterally at rates of centimeters per year, and then are subducted beneath continents and oceanic plates to be remelted and destroyed.

The continents, produced much earlier in Earth's history, ride passively on the laterally migrating plates, sometimes colliding to produce huge mountain ranges such as the Himalayas. The rapid rate of this recycling, combined with water-dominated erosion of the continents, obscured or destroyed most of the record from the first half of Earth's 4.5-billion-year history. Why does Earth have plate tectonics, and when did it start? What was it like before plate tectonics? How did the continents form? What were the formative years of Earth's history like, and what childhood events shaped its current state?

Scientists began to look to the solar system for answers to these fundamental questions. Planetary bodies changed from astronomical objects to geological objects. Scientists hoped the nature, distribution, and age of surface features could tell us about the geological processes that shape the surfaces, and thus about the evolution of planetary interiors and the history of the planets.

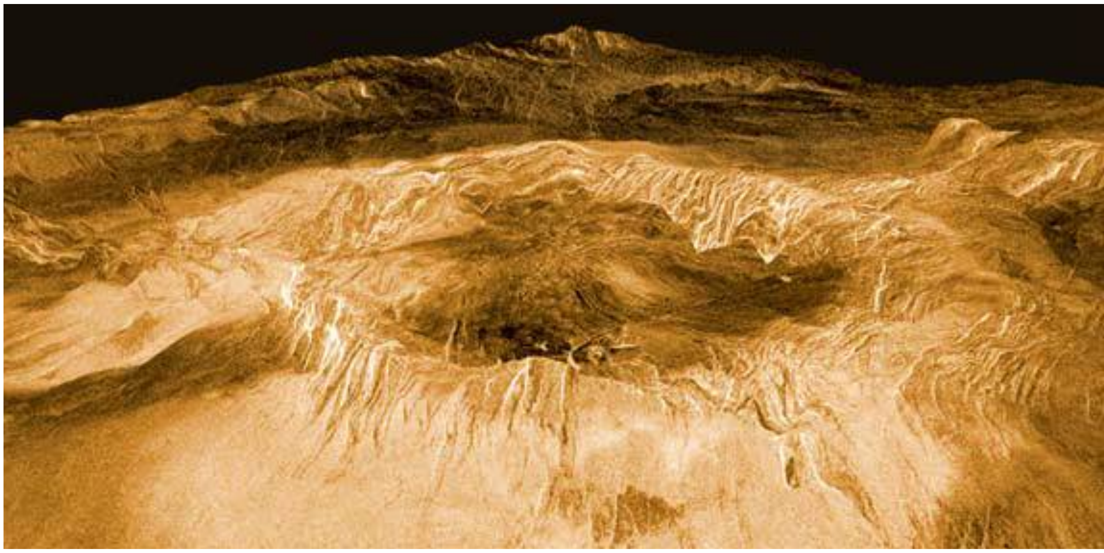
Exploring the smaller terrestrial worlds — the Moon, Mercury, and Mars (each less than about half the diameter of Earth and Venus) — showed they, unlike Earth, are characterized by a single global lithospheric plate. These small planets have a large ratio of surface area to volume, so they efficiently radiate heat to space. Their lithospheres thickened and stabilized early in their history, creating one-plate planets.

This lack of recycling meant the missing chapters of Earth's history were laid out for us to examine. Planetary scientists began to understand the profound influence of impact cratering early in lunar history: The heat and destruction provided by abundant and large impacts differentiated these bodies' internal compositions, created crusts, and produced the initial landscapes. Most of these impact craters were preserved for the remainder of solar system history. The lunar maria, the huge volcanos of Mars, and the enigmatic plains of Mercury all point to volcanism as a fundamental process in this early history. Scientists came to see the smaller terrestrial bodies as evolving differently from Earth largely because they are smaller.

The tale of Venus

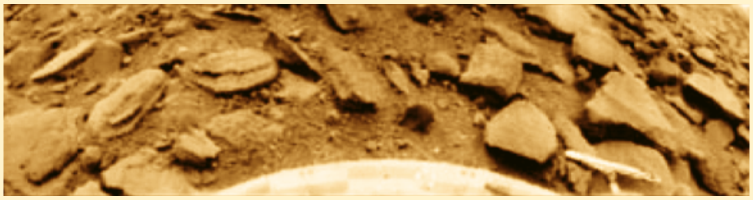
Venus offered a different take. Its size, density, and position in the solar system are similar to Earth's. Does Venus have plate tectonics? All planetary objects must lose their internal heat somehow. Small, one-plate bodies simply radiate the heat to space. Earth does it by plate recycling. And some, like Jupiter's incredibly active moon Io, directly transfer hot material from its interior by volcanism.

Would the average age of Venus' surface show it to be old, like the one-plate planets, or young like Earth? The number of impact craters would tell that tale. If Venus had earthlike continents, they might provide clues as to how

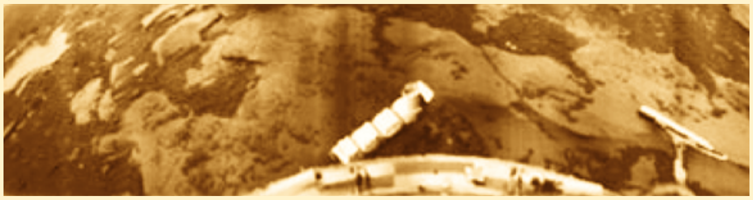


▲ **CIRCULAR DEFORMATION BELTS,** **called coronae, apparently form when a plume of rising mantle material lifts the surface. When the plume eventually wanes, the structure's interior collapses.** NASA/JPL

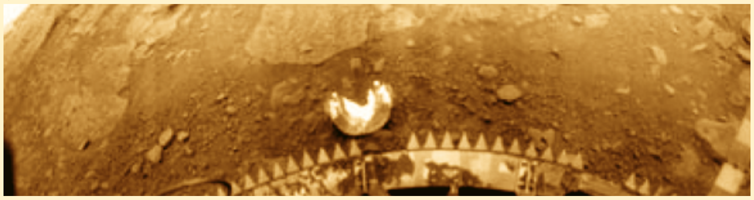
▼ Venera 9 — 1975



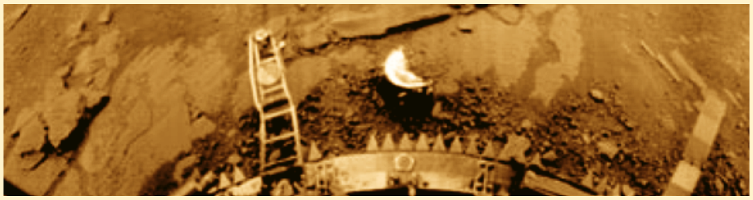
▼ Venera 10 — 1975



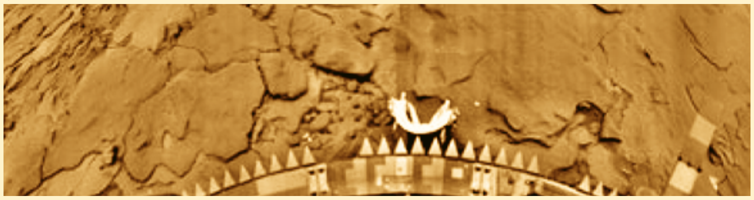
▼ Venera 13 — 1981



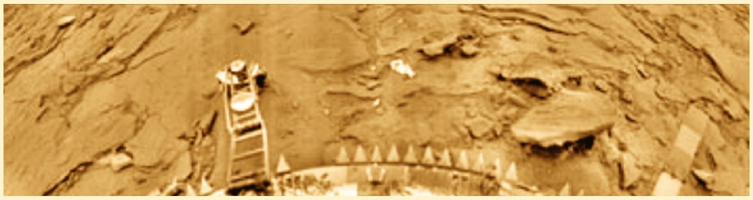
▼ Venera 13 — 1981



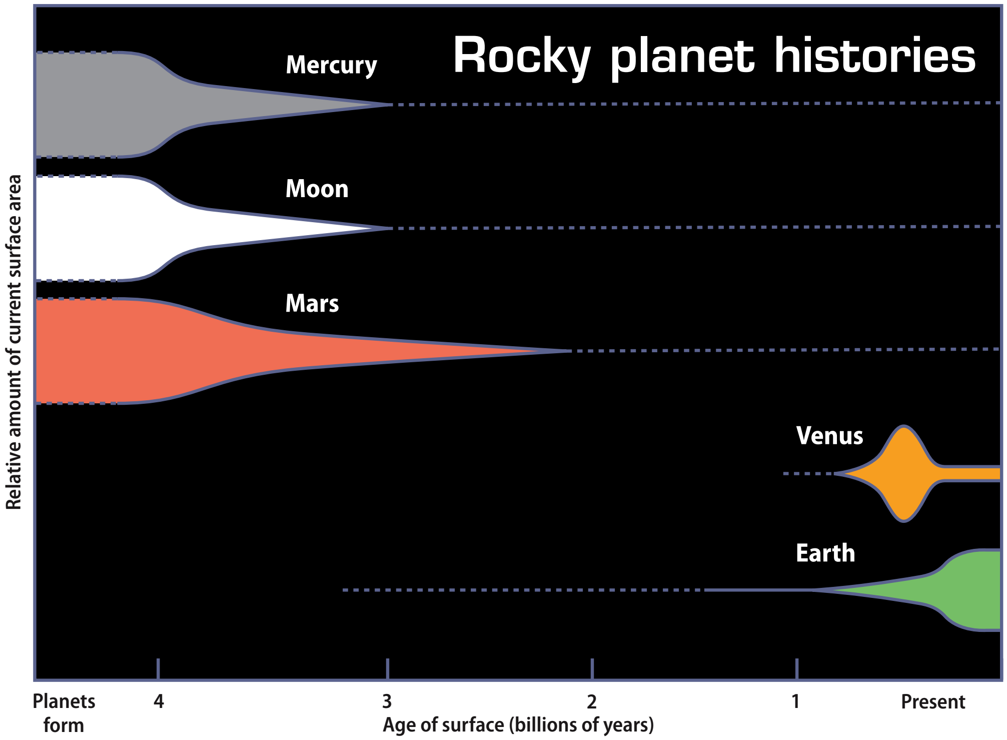
▼ Venera 14 — 1981



▼ Venera 14 — 1981



▲ **VENUS' SURFACE APPEARED TO HUMANS FOR THE FIRST TIME through the camera lenses of the Soviet Union's Venera spacecraft. These images reveal the blocky, plate-like rocks and soils typical of Venus' surface at four of the landing sites.** RUSSIAN ACADEMY OF SCIENCES/DON P. MITCHELL



▲ **EARTH AND VENUS evolved far differently from the one-plate planets. All planets formed 4.5 billion years ago. Mercury, the Moon, and Mars have changed little in the past 3 billion years. Earth and Venus, however, preserve none of their original crust. Volcanism globally resurfaced Venus 500 million years ago.** *ASTRONOMY*: THEO COBB

Earth's continents formed. Maybe Venus' evolution represents a transition between that of one-plate planets and Earth. Or perhaps it represents something entirely different.

Obscured by clouds, Venus' surface remained hidden, and the exploration and answers to these questions lagged behind. They would have to wait for the advent of technology that could unveil the planet's secrets.

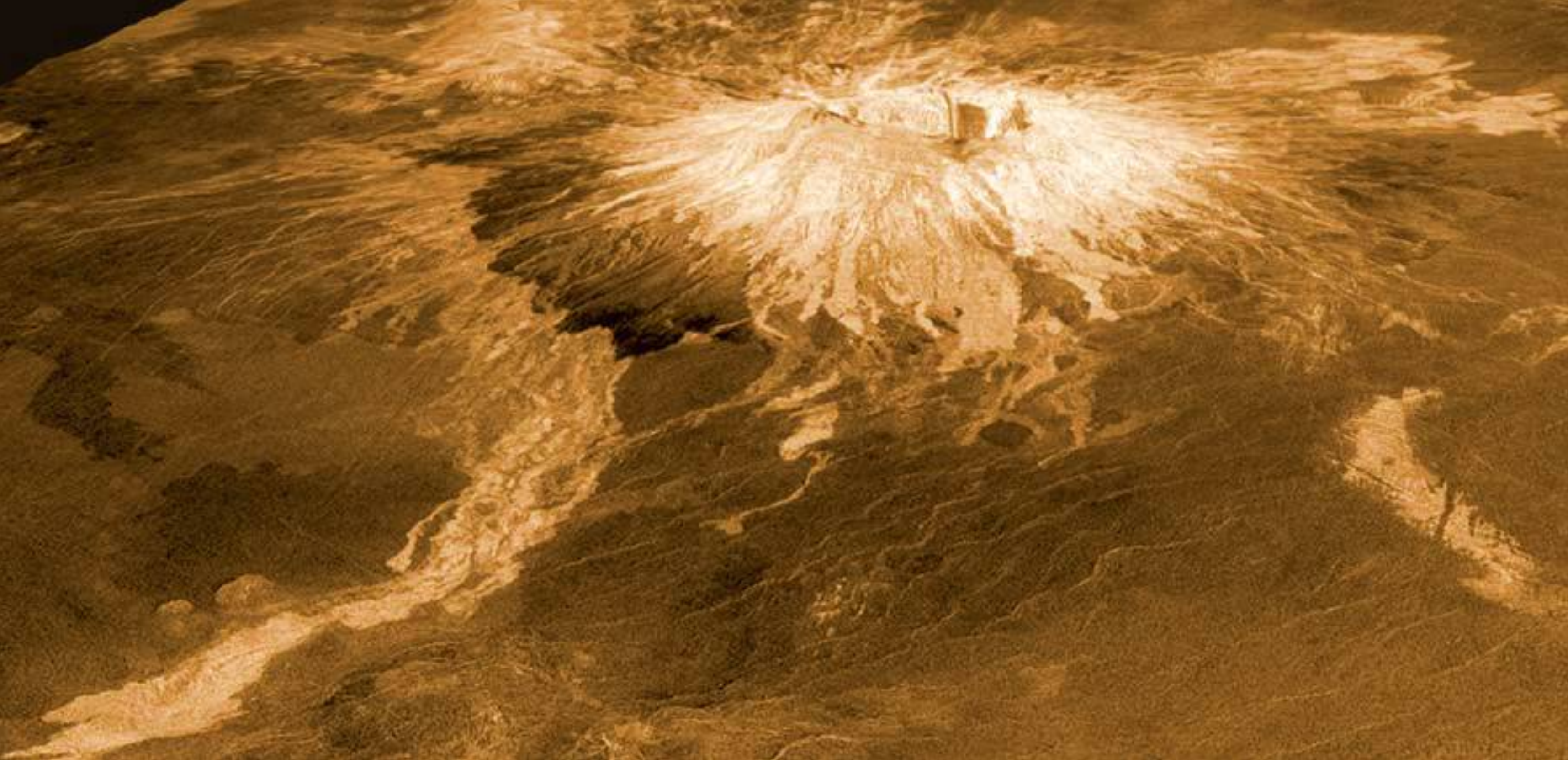
Exploration of Venus by the Soviet Union and the United States slowly revealed elusive surface features. Beginning in 1961, Soviet atmospheric probes descended all the way to the surface. In the 1970s, landers began to return images from the surface and analyze the lavalike basaltic rocks.

Earth-based radar observations, with resolutions as high as about 3 miles (5 kilometers), began to provide some broad geological context for these landing sites. Both familiar and unfamiliar planetary landscapes started to emerge.

Scientists saw features that resemble impact craters, but they also found lots of unusual, larger circular features. Rift zones like those on Mars emerged, but so did distinctive, banded mountains reminiscent of earthly mountains created by plate tectonics. Volcanic flows and edifices also showed up, but the radar resolution wasn't good enough to convey their abundance and role in geological evolution.

In the late 1970s, the United States placed the Pioneer-Venus spacecraft in orbit. It revealed Venus' global topography at resolutions of about 60 miles (100 km). Continentlike uplands, such as Ishtar and Aphrodite Terra, were separated by seafloorlike lowlands, sharpening the debate about whether Venus had plate tectonics. In 1983, the Soviet Union orbited two spacecraft, Venera 15 and 16, which measured surface heights and took images with about 1 mile (1 to 2 km) resolution of roughly 30 percent of the planet's northern hemisphere.

These data completed the transition of Venus from an astronomical to a geological object. They revealed large expanses of topographically high, continentlike terrain that had been highly deformed. Planetary scientists named this type of feature "tessera" for its tilelike nature. Folded mountain belts surrounded highland plateaus,



▲ **MAJOR SHIELD VOLCANOS dot Venus' surface. This view shows the 2-mile-high (3 km) Sapas Mons. Venus' scalding surface temperature causes lava to flow greater distances than it does on Earth, and volcanos typically are lower and broader.** NASA/JPL

much like convergent plate boundaries on Earth. Large circular features, named "coronae," appeared to represent upwelling from the interior and deformation of the surface, implying active convection in the planet's mantle.

Impact craters, although seemingly fewer than on the smaller terrestrial planets, showed unusual ejecta deposits. Lots of large volcanos showed up, along with tens of thousands of small shield volcanos.

A treasure trove of information, to be sure. But scientists still didn't know what lurked on the other 70 percent of the planet's surface. Perhaps the rest of Venus offered hints of an ancient, heavily cratered surface, divergent plate boundaries, or rampant active volcanism.

Magellan hits the scene

In May 1989, the United States launched the Magellan spacecraft to Venus. Its mission: To map the entire surface with radar and to determine global topography. Magellan's images have resolutions of 330 to 660 feet (100 to 200 meters), sufficient for scientists to identify key geological features and understand the processes that formed them. These images also helped establish the features' relative ages, and thus the planet's geological history.

In the early 1990s, planetary geoscientists stood on the verge of a major understanding of Venus. Slowly, orbit by orbit, Magellan revealed Venus' surface in long, narrow, and exceedingly sharp swaths. As the planet slowly rotated beneath the orbiting spacecraft, scientists realized that a wide diversity of volcanic landforms dominate the surface. Huge shield volcanos, vast volcanic plains, tens of thousands of small shield volcanos, hundreds of biscuitlike domes (some more than 18 miles [30 km] in diameter), tick-shaped edifices, thousands of unusual fluidlike lava flow fronts, steep-sided viscous-looking flow fronts, and pits and calderas of unparalleled diversity cover Venus. This planet is clearly a volcanologist's dream.

Soon thereafter, scientists realized there were no regions of densely packed impact craters, which would have signified surviving areas of ancient crust. Instead, the surface shows only a smattering of craters. By mission's end, Magellan had found only about 1,000 craters.

This news startled planetary scientists. Taken at face value, this low number of craters meant the average age of Venus' surface is less than 1 billion years — similar to Earth's average age and billions of years younger than those of the smaller terrestrial planets. Was this proof that earthlike plate tectonics also characterize Venus' surface? If so, perhaps Venus — at least underneath its dense, carbon-dioxide-rich atmosphere — is Earth's twin after all.

Once Magellan completed its mapping, scientists plotted the distribution of impact craters.

STATISTICS: Venus vs. Earth

	Venus	Earth comparison
Mass	10.73 trillion trillion pounds	81.5% of Earth's
Diameter	7,521 miles	94.9%
Density	5.24 grams/cc	95.1%
Weight of 150-lb person	136 pounds	90.5%
Distance from Sun	67.24 million miles	72.3%
Orbital period	224.70 days	61.5%
Length of day	2,802 hours	11,675%

Mass: Total mass (1 trillion = 10^{12}); **Diameter:** Equatorial diameter; **Density:** Average density in grams per cubic centimeter (water = 1); **Distance from Sun:** Average distance; **Orbital period:** Sidereal period; **Length of day:** Average time between successive noons; **Earth comparison:** Ratio of Venus' to Earth's value.

They anticipated finding regions with fewer craters, the likely sites of new crust and divergent plate boundaries. They also expected to see areas with more abundant craters, where older crust and convergent boundaries would lie.

To everyone's surprise, the global distribution of impact craters looked to be completely random. Sure, the surface was young like that of the active Earth, but the seemingly random crater distribution meant plate tectonics could not have occurred on Venus in the last several hundred million years. Obviously, whatever process produced this global configuration is unique in the inner solar system.

Examining the nature of the impact-crater population further startled planetary scientists.

Unlike impact craters on other planets, only a few of Venus' craters show signs of degradation and crater aging caused by tectonism or volcanic burial. This presented a seemingly inescapable conundrum: Globally extensive volcanism had created Venus' surface fairly recently, and in the process had destroyed the earlier historical record and its associated impact craters. But, by virtue of the pristine nature of the vast majority of impact craters, the volcanism and related tectonism must have ceased soon after its global emplacement. Otherwise, we would expect to see craters in all states of degradation and flooding.

A catastrophic Venus?

In the 18th century, geologists were instrumental in providing an alternative view of Earth's history to that of the biblical flood. They emphasized the slow, methodical work of geological forces in a "uniformitarian" view of Earth evolution, in contrast to a biblical, weeklong creation and catastrophic flood. Most geoscientists consider it anathema to propose a seemingly biblical catastrophe to explain observed events.

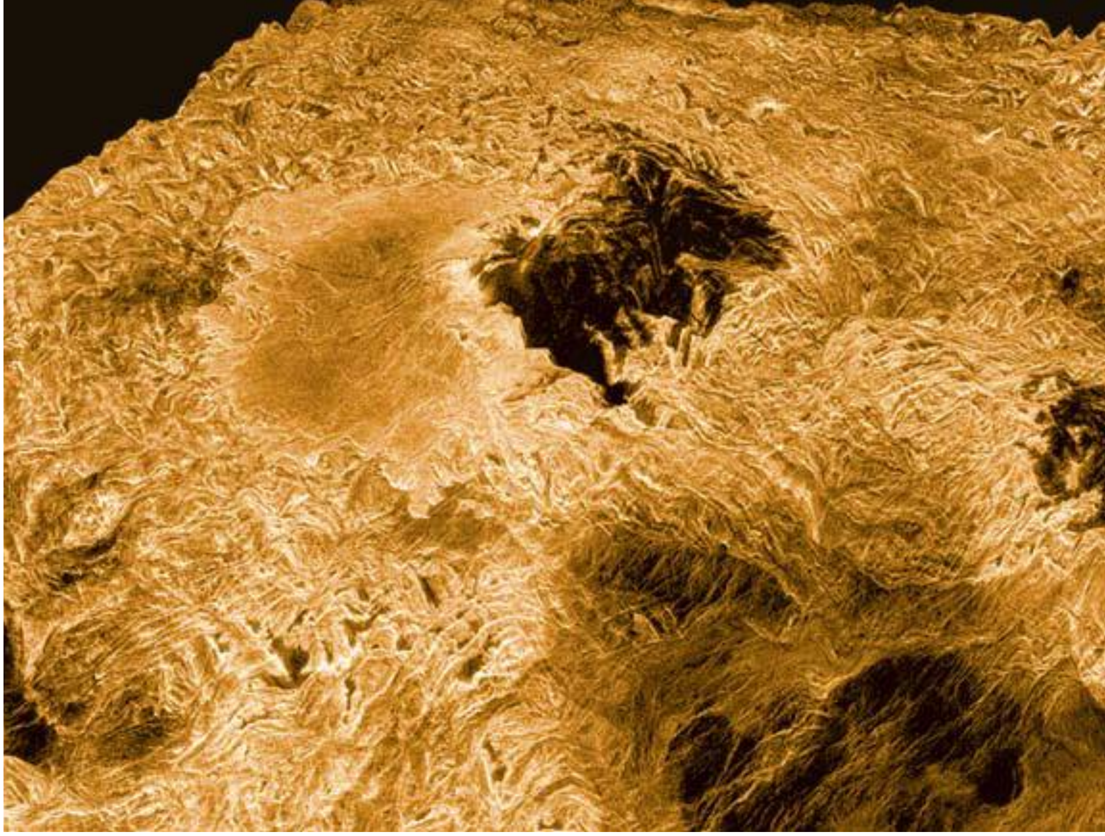
Nonetheless, the Magellan observations seemed to call for just such a hypothesis. Several scientists proposed that a catastrophic volcanic resurfacing wracked Venus fairly recently, that it had ended rapidly, and that little activity has taken place since.

Others hypothesized that Venus underwent episodic plate tectonics, with periods of active global plate tectonics punctuated by phases when it behaved as a one-plate planet. In this view, Venus currently enjoys an intervening quiescent period.

Still others looked to the vertical growth of crust on one-plate planets and realized that eventually, with enough internal energy, piles of volcanic materials will become gravitationally unstable, founder, and overturn. This will lead to global deformation and volcanic resurfacing, followed by a period of relative quiescence.

Some geophysicists looked to the thermal evolution of planets and hypothesized that Venus had just crossed the boundary between a plate-tectonic-dominated "mobile-lid" regime and a relatively quiescent "stagnant-lid" regime, a scenario some scientists predict will happen to Earth in its future.

Geologists began to study the sequence of events in the latter part of Venus' history still preserved in the surface morphology. Through detailed geological mapping, they found the highly deformed tessera terrain predates the vast volcanic plains. They also saw some indication for a sequence of events in both volcanic units and tectonic features.



▲ **STEEP-SIDED FLOWS** in Aphrodite Terra hint that the tessera terrain underlying the flows may have a composition similar to Earth's continents. The thick flows occur at the summit of these highlands, which themselves rise 2 to 3 miles (4 to 5 km) above the surrounding plains. NASA/JPL

Many of these observations seemed to support a distinctive sequence in Venus' history: an initial period of intense deformation followed by global volcanism and then relative quiescence. But controversy erupted. Other researchers dubbed this interpretation of Venus' history as "directional," and instead proposed a "non-directional" theory in which geological features and events formed essentially randomly in time.

VOLCANISM CREATED VENUS' SURFACE FAIRLY RECENTLY AND DESTROYED THE EARLIER RECORD.

Today, the understanding of Venus' history lies in successfully merging the global geological mapping of Venus with the many theories for the geodynamical processes that might explain these observations. The stakes are high: They could go a long way toward our understanding of the nature and evolution of earthlike planets. They could tell us whether Earth underwent or could undergo such a catastrophic overturn and whether plate tectonics on Earth started in such a manner.

Venus also might tell us whether Earth undergoes episodic plate tectonics — and if this is how our continents formed. Perhaps Venus will provide insight into Earth's Archean eon, a formative period of Earth's history whose record has largely been destroyed.

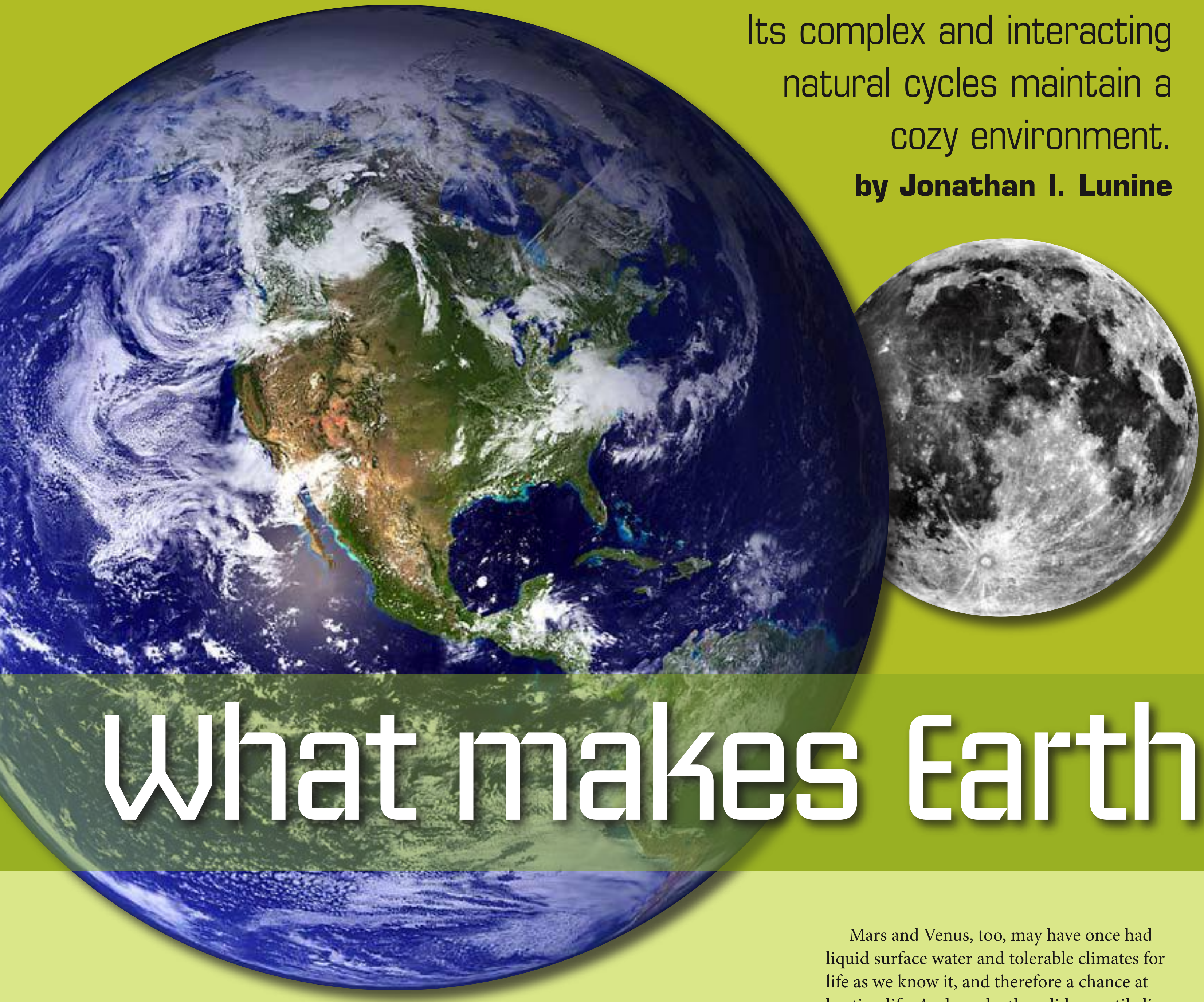
In addition to further analyzing the vast amounts of data they have in hand, scientists are busy designing experiments to address these remaining questions. The only mission currently operating, the European Space Agency's Venus Express, is orbiting the planet to study the nature and evolution of its atmosphere.

Scientists worldwide are studying a range of possible missions. One idea is to land in the tessera terrain to assess its composition. Others champion balloons with reversible fluids that could descend and ascend to make surface and atmospheric measurements over wide areas of the planet. Long-term surface stations and rovers could also be in the mix. And, ultimately, missions might even return rocks and soil from Venus for dating and analysis.

Venus, once thought to be Earth's twin, may instead be a long-lost sibling. Our sister planet could provide a fundamental, but forgotten, perspective on our family history. ◘

Earth is more than just a pretty face. Its complex and interacting natural cycles maintain a cozy environment.

by Jonathan I. Lunine



What makes Earth

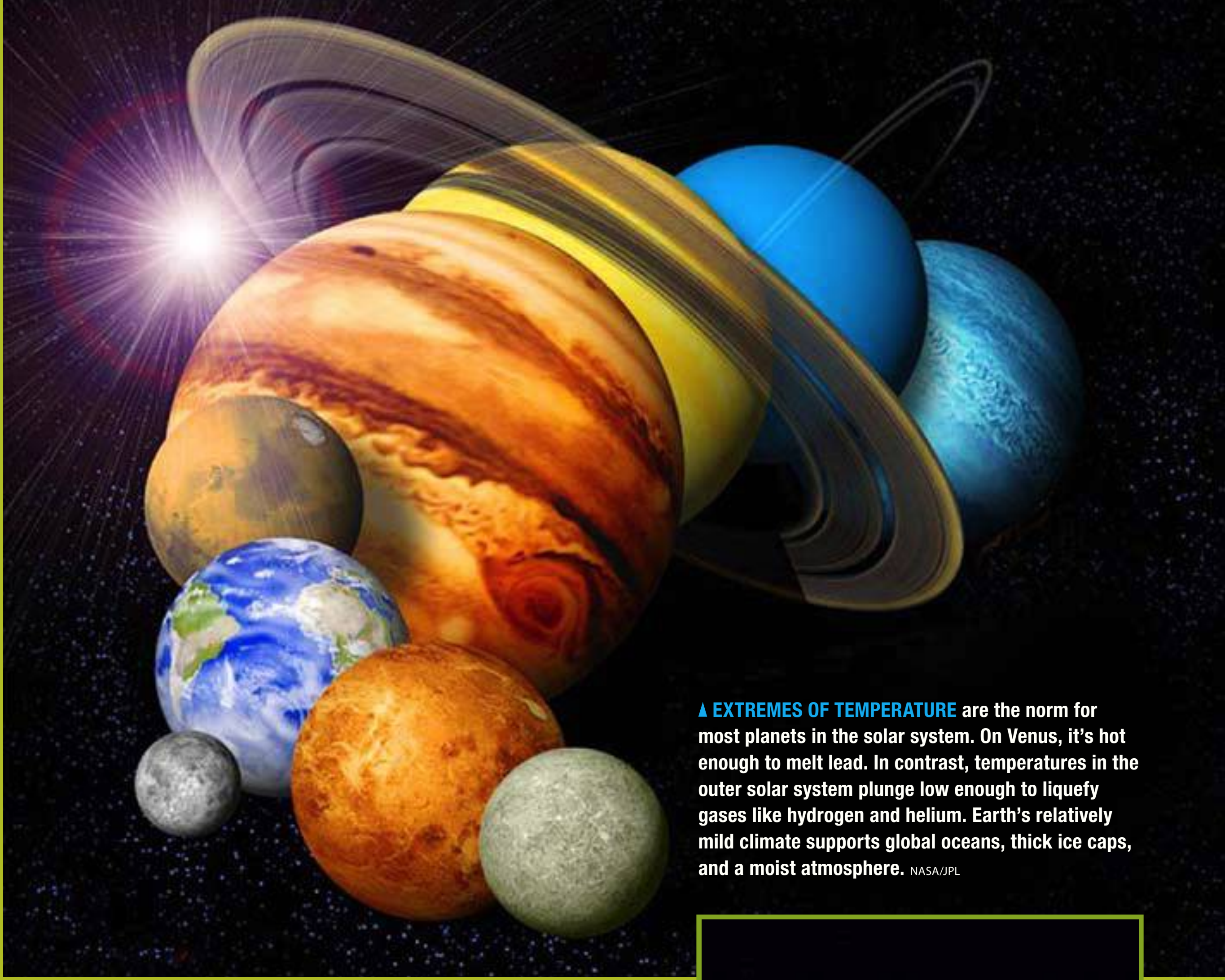
Earth is the third planet from the Sun, one of eight major planets that orbit our rather ordinary star on the outskirts of the Milky Way Galaxy. And Earth is the only one of the planets known to host life. But why?

It's not just about the water, although Earth's abundant water helps make it a living planet. Nor is Earth welcoming to life only because it lies a comfortable distance from the Sun — not too hot, not too cold.

Mars and Venus, too, may have once had liquid surface water and tolerable climates for life as we know it, and therefore a chance at hosting life. And maybe they did — until climate change wiped it out.

Perhaps the one thing that makes Earth most remarkable in the solar system is that it

▲ EARTH IS UNIQUE in the solar system as the only planet known to host life, largely because of global geological processes that have combined to maintain a livable climate for billions of years. Unlike other planets with moons, Earth has but a single, large natural satellite — the Moon. It's an oddity in a solar system swarming with moons — about 169 at last count. EARTH: RETO STÖCKLI & ROBERT SIMMON (NASA GODDARD SPACE FLIGHT CENTER)/ USGS/DMSP; MOON: LICK OBSERVATORY



▲ **EXTREMES OF TEMPERATURE** are the norm for most planets in the solar system. On Venus, it's hot enough to melt lead. In contrast, temperatures in the outer solar system plunge low enough to liquefy gases like hydrogen and helium. Earth's relatively mild climate supports global oceans, thick ice caps, and a moist atmosphere. NASA/JPL

right for life?

has remained a living world, continuously, for billions of years. Despite a few close calls with global mass extinction, life has endured. To comprehend why requires understanding the global biological, geological, and chemical systems that maintain a relatively stable, welcoming environment for terrestrial life.

Earth in the solar system

Although life makes Earth unique in the solar system, other factors also distinguish our home world from its neighbors. Earth is among the four members of the inner solar system that are rocky and have metal-rich centers. The remaining four major planets are gaseous spheres with varying amounts of rock and ice.

The outer planets have a variety of moons, two of which — Jupiter's Ganymede and Saturn's Titan — are larger than Mercury. Among major planets with moons, Earth is the only one with a single example — Luna, or simply the Moon.

The Moon is about 30-percent smaller than Mercury, and made almost entirely of rock with little metal. Its chemical composition and large size are best explained if the Moon formed when a Mars-sized impactor gouged out a chunk of Earth. Our satellite's birth must have happened in Earth's infancy, judging from the similarity in the age of Moon rocks and primitive meteorites, which existed at the time the planets formed.

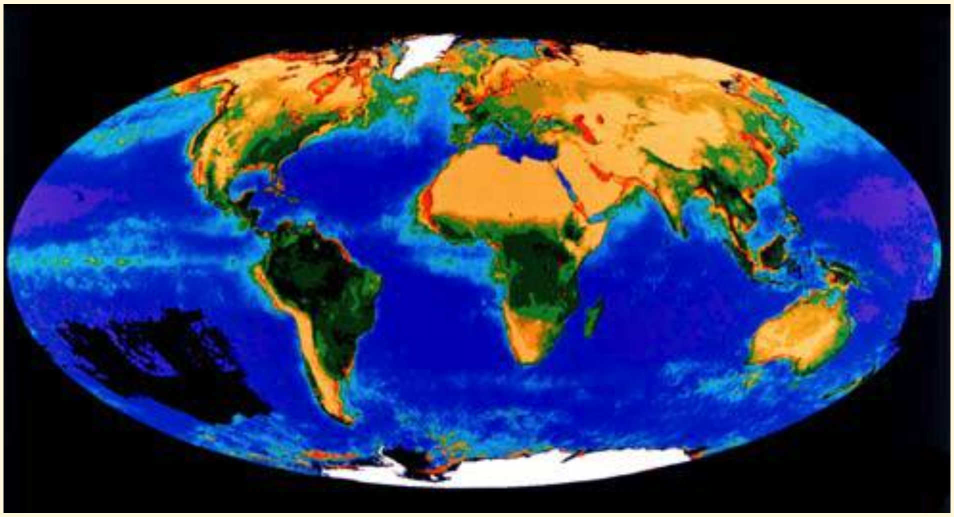
▲ **EARTH'S OXYGEN-RICH ATMOSPHERE** sustains most life-forms that inhabit the planet's vast biosphere. Photosynthesizing plant life continually replenishes the oxygen supply. On July 14, 1995, astronauts on the space shuttle snapped this image of the Moon rising above Earth's ocean of air. NASA

The ocean of air

Earth is one of only four planets and moons in the solar system to have a substantial atmosphere. The others are Mars, Titan, and Venus.

The air on Titan and Venus is thicker than Earth's, whereas the atmosphere on Mars is thinner. Nitrogen predominates in the atmospheres

SATELLITE SNAPSHOTS SHOW EARTH'S BIOSPHERE IN OPERATION



▲ THIS IMAGE REPRESENTS **humans' first look at the global biosphere — the total area inhabited by living organisms. Green and red coloring reflects the activity of ocean plankton and land plants.** NASA

NASA imaging scientists created this map of the global biosphere by combining 3 years of data from the Advanced Very High Resolution Radiometer (AVHRR) instrument aboard the NOAA-7 satellite, and 20 months of data collected by the Coastal Zone Color Scanner instrument aboard the Nimbus-7 satellite from 1978 to 1980.

As plants use sunlight to manufacture carbohydrates from water and carbon dioxide, they produce the green pigment chlorophyll. These organisms include ocean phytoplankton, which are microscopic plants that grow near the ocean surface and form the base of the marine food web. Red and orange colors indicate areas of high plankton concentrations. Yellow and green represent areas of moderate concentration.

On the continents shown in the map, the colors indicate chlorophyll production in trees and other plants. The lighter shades of green highlight tropical and subtropical forests, temperate forests, farmlands, and drier savannas and pampas. The dark green areas are rain forests with the highest potential for chlorophyll production.

In short, this extraordinary image is a snapshot of Earth's biosphere harnessing sunlight, water, and carbon to make food for itself. In the process, the biosphere produces oxygen that sustains life elsewhere in the food web — like you and me.

of both Earth and Titan. In contrast, carbon dioxide constitutes virtually all of the gaseous envelopes of Mars and Venus.

But what truly sets Earth apart is its abundance of free oxygen, which comprises about 21 percent of the atmosphere. The remainder is approximately 78 percent nitrogen, plus 1 percent carbon dioxide, water, and argon.

Plant photosynthesis replenishes Earth's oxygen. During the process, plants use sunlight to convert carbon dioxide and water into carbohydrates, which are the foundation of the global food chain.

Were photosynthesizing life to cease completely, free-floating oxygen would react with rocks, volcanic gases, and biological materials and virtually disappear in a geologically brief period of time. Therefore, Earth's chemical composition remains stable — and supportive of terrestrial life — because of the constant resupply of oxygen from biological activity.

Cozy greenhouse

Earth's atmosphere is key to maintaining a warm surface that allows liquid water, and therefore life, to exist. The daytime temperature of the atmosphere at Earth's surface — averaged across the seasons, the day/night (diurnal) cycle, and changing latitudes — is 46° Fahrenheit (8° Celsius). In contrast, an airless sphere with Earth's brightness and distance from the Sun would have a surface warmth of only 1° F (–17° C). This chilly "effective" temperature would create largely frozen oceans.

IF PHOTOSYNTHESIS CEASED COMPLETELY, FREE-FLOATING OXYGEN WOULD VIRTUALLY DISAPPEAR IN A GEOLOGICALLY BRIEF PERIOD OF TIME.

What elevates Earth's surface temperature is a process called the greenhouse effect. The mechanism by which it warms Earth's atmosphere differs substantially from that of a glass-enclosed greenhouse, but the image serves as a useful shorthand.

The atmosphere is largely transparent to the visible-light wavelengths in sunlight. Therefore, sunlight streams down, impeded only by clouds, to Earth's lower atmosphere and surface. Oceans and land absorb the energy and then re-emit it as heat in the form of infrared light.

However, the atmosphere is not transparent to infrared light, so it can't directly radiate out into space. Gases such as carbon dioxide, water, and methane absorb infrared light. These gases then re-emit the energy back out into the atmosphere as infrared. This process repeats many times along the energy's journey to space.

The greenhouse effect's repeated absorption and emission of infrared energy warms the atmosphere. However, the warming is greatest near the surface, where the atmosphere is densest. As a result, the temperature is higher closer to the ground, where the air is denser, and cooler at higher altitudes. This, as we will see later, has important consequences for climate.

Atmospheric rainmaker

The greenhouse effect has a significant impact on the troposphere, the atmospheric layer closest to the surface and an average of 7.5 miles (12 kilometers) thick. Greenhouse heating drives turbulent mixing, or convection, in the lower atmosphere.

Because the atmosphere cools with increasing altitude, the air in the troposphere is unstable. Warm air rises in columns, cools, and then sinks. Water vapor in the rising air condenses to form clouds. In the process, the vapor releases heat, which helps to drive vertical air circulation in the troposphere.

Condensation of rising humid air commonly produces towering cumulonimbus clouds. When they evolve into thunderstorms, such clouds produce heavy rain and cool the lowermost atmosphere.

STATISTICS: Earth

	Earth
Mass	13.17 trillion trillion pounds
Diameter	7,926 miles
Density	5.52 grams/cc
Distance from Sun	92.96 million miles
Orbital period	365.26 days
Length of day	24 hours

Mass: Total mass (1 trillion = 10^{12}); **Diameter:** Equatorial diameter; **Density:** Average density in grams per cubic centimeter (water = 1); **Distance from Sun:** Average distance; **Orbital period:** Sidereal period; **Length of day:** Average time between successive noons.

Earth's surface receives more sunlight at the equator than at the poles. Warm air flows away from the equator toward higher, cooler latitudes, where it sinks. This rising action aids equatorial convection, whereas sinking air at about 30° north and south latitudes suppresses it.

Closer to the poles, other large-scale circulation patterns occur. Systems of high and low pressure — formed by the twisting motion that Earth's rotation imposes on the heated atmosphere — create bands of easterly or westerly flowing air at different latitudes.

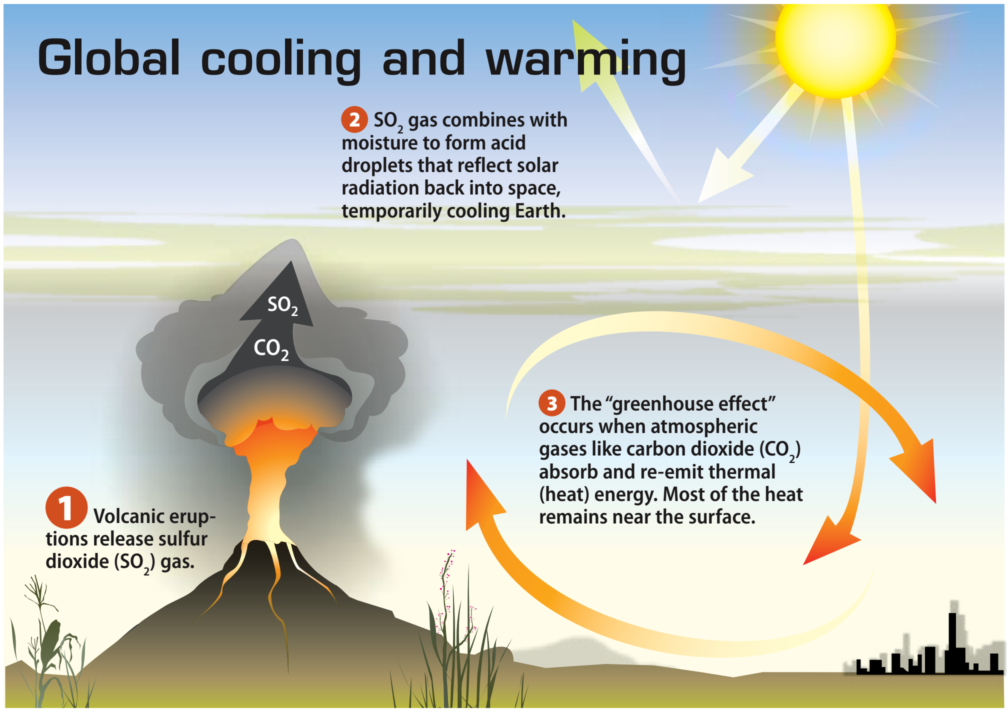
Water, water everywhere

Frequent thunderstorms are a distinctive feature of our home planet. This is fortunate, because storms keep water continuously in motion between the land and the oceans. This global system is called the water cycle.

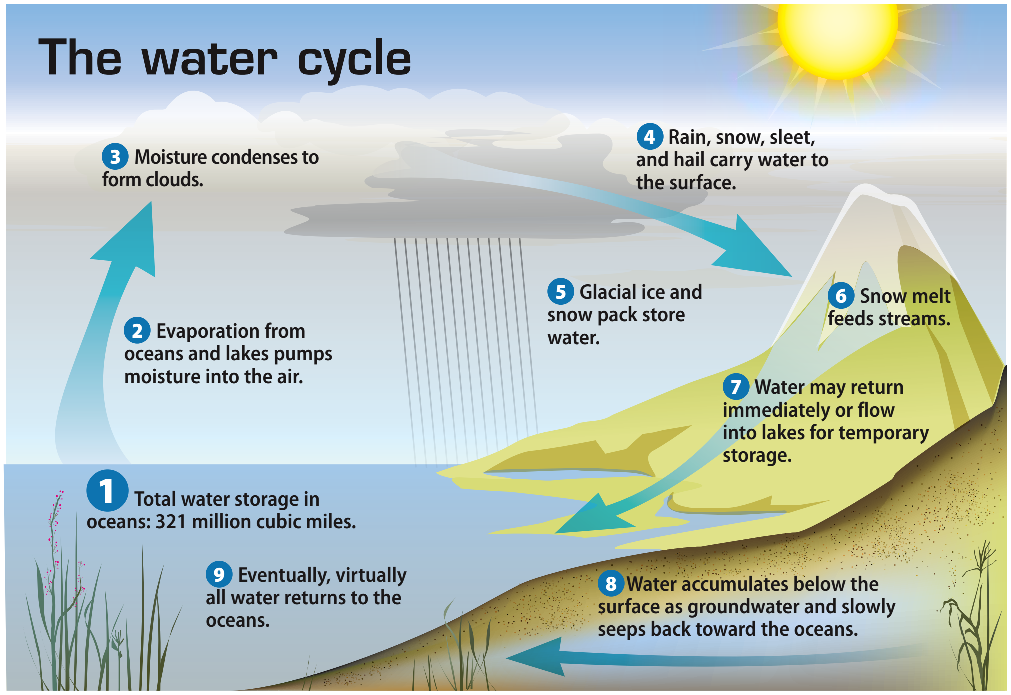
Moisture rises from the oceans, flows toward land, and condenses into precipitation. On the surface, water either flows back into the sea through rivers or collects for some period of time in glaciers, snow pack, lakes, or aquifers. Data from planetary probes show that an analogous system on Titan shuttles methane from large lakes to the land and back again.

The water cycle plays a key role in sustaining life in countless ways. In one example, the erosion of rock by streams carries minerals into the sea. Tiny creatures called diatoms use the minerals to build their shell-like bodies. And, of course, the water cycle distributes moisture to countless forms of land life.

The oceans are part of a system that transports heat around the world along what is sometimes called the "global conveyor belt" system of currents. Along with atmospheric circulation, the ocean currents help to regulate the global climate within relatively narrow bounds. It's a key element of Earth's great thermostat.


Global cooling and warming
2 SO_2 gas combines with moisture to form acid droplets that reflect solar radiation back into space, temporarily cooling Earth.
SO_2
CO_2
3 The "greenhouse effect" occurs when atmospheric gases like carbon dioxide (CO_2) absorb and re-emit thermal (heat) energy. Most of the heat remains near the surface.
1 Volcanic eruptions release sulfur dioxide (SO_2) gas.

THE GREENHOUSE EFFECT refers to warming of the atmosphere caused by the presence of certain gases, such as carbon dioxide and methane. Without it, Earth would be much colder on average, with largely frozen oceans. Some gases, such as sulfur dioxide (SO_2), produce short-term cooling. *ASTRONOMY*: ROEN KELLY

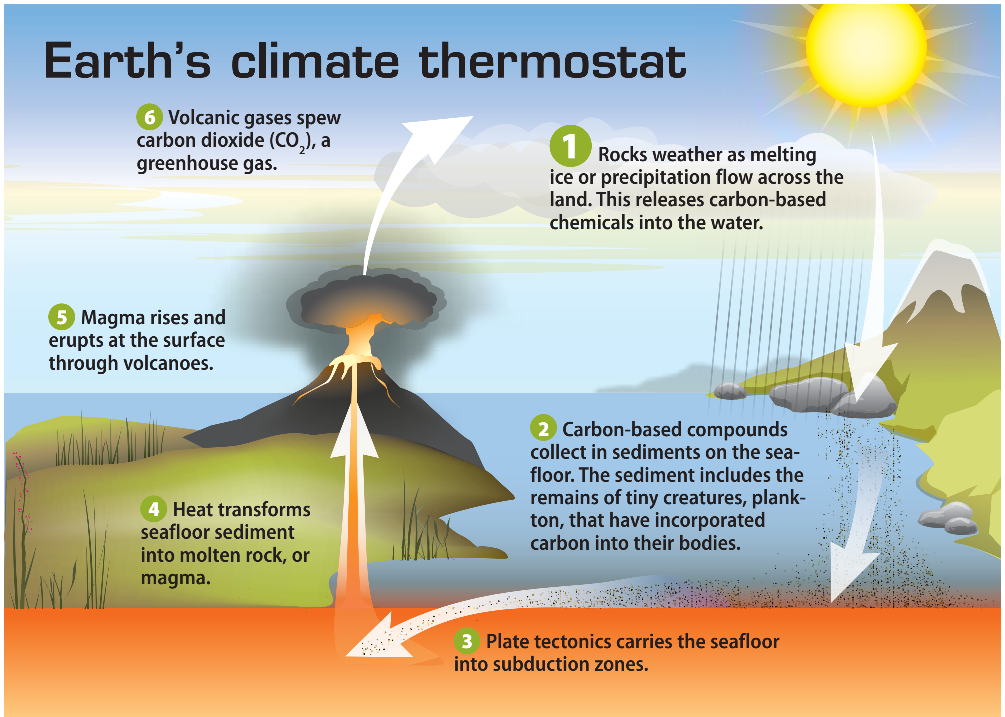

The water cycle
3 Moisture condenses to form clouds.
4 Rain, snow, sleet, and hail carry water to the surface.
5 Glacial ice and snow pack store water.
6 Snow melt feeds streams.
2 Evaporation from oceans and lakes pumps moisture into the air.
7 Water may return immediately or flow into lakes for temporary storage.
1 Total water storage in oceans: 321 million cubic miles.
9 Eventually, virtually all water returns to the oceans.
8 Water accumulates below the surface as groundwater and slowly seeps back toward the oceans.

WATER IS ALWAYS IN MOTION on Earth — in the atmosphere, on the surface, and below ground. The movements occur over seconds to millions of years. Along the way, water changes between solid, liquid, and gas. The water cycle helps maintain a habitable planet. *ASTRONOMY*: ROEN KELLY

The solid Earth

Volcanic eruptions, earthquakes, and the birth of mountain ranges, basins, and valleys all trace their origins to the vast reservoir of heat in Earth's interior that is slowly leaking out. Some of this heat is left over from the planet's formation. Some of the heat traces to the radioactive decay of uranium and other elements embedded in deep rock.

Fortunately for life, Earth's internal heat drives a process called plate tectonics. This process, in turn, contributes to the global thermostat


Earth's climate thermostat
6 Volcanic gases spew carbon dioxide (CO_2), a greenhouse gas.
1 Rocks weather as melting ice or precipitation flow across the land. This releases carbon-based chemicals into the water.
5 Magma rises and erupts at the surface through volcanoes.
2 Carbon-based compounds collect in sediments on the seafloor. The sediment includes the remains of tiny creatures, plankton, that have incorporated carbon into their bodies.
4 Heat transforms seafloor sediment into molten rock, or magma.
3 Plate tectonics carries the seafloor into subduction zones.

▲ **THE GLOBAL CLIMATE THERMOSTAT, involving tectonic plate motion, water, and volcanism, has maintained a relatively stable climate for billions of years. It turns down the heat when global average temperatures rise, and turns up the heat when the climate cools — just like a home thermostat.** *ASTRONOMY*: ROEN KELLY

WHERE IS EARTH'S WATER?

Water source	Water volume in cubic miles	Water volume in cubic kilometers	Percent of Earth's total water
Oceans, seas, and bays	321,000,000	1,338,000,000	96.5
Ice caps, glaciers, and permanent snow	5,773,000	24,064,000	1.74
Groundwater	5,614,000	23,400,000	1.7
Fresh	2,526,000	10,530,000	0.76
Saline	3,088,000	12,870,000	0.94
Soil moisture	3,959	16,500	0.001
Ground ice and permafrost	71,970	300,000	0.022
Lakes	42,320	176,400	0.013
Fresh	21,830	91,000	0.007
Saline	20,490	85,400	0.006
Atmosphere	3,095	12,900	0.001
Swamp water	2,752	11,470	0.0008
Rivers	509	2,120	0.0002
Biological water (all life)	269	1,120	0.0001
Total	**332,500,000**	**1,386,000,000**	**100**

SOURCE: U.S. GEOLOGICAL SURVEY

that regulates Earth's climate on time scales of millennia. Plate tectonics is probably why life on Earth is still living, and not simply part of the fossil record. Here's how it works.

Early in Earth's history, internal heat warmed the interior enough to allow iron to sink to the core. Lighter elements rose to shallower depths to form the mantle, Earth's middle layer. The mantle slowly flows and deforms similar to the way the glass in ancient windows gradually sags under gravity's tug.

The crust, Earth's least-dense rock layer, floats on top of the mantle. Crustal rock is rigid and brittle, like an eggshell.

The crust and the uppermost layer of the mantle are broken into vast fragments called tectonic plates. Where a dense ocean plate meets a continental plate, the former noses downward, forming a subduction zone. The plate plunges thousands of miles. Ultimately, it melts and becomes part of the mantle in a kind of global recycling process.

At plate boundaries known as spreading centers, the plates move apart. Molten rock wells up from below to fill the space. Iceland sits atop such a spreading center, which is why the land is entirely volcanic in origin.

Earth's plates move away from spreading centers like conveyor belts, with new crust rising and old crust sinking. The continents and ocean basins ride on top of the plates.

Earth appears to be unique in today's solar system for having active plate tectonics. Water plays an important role in plate tectonics, too. Wet sediment on the ocean floor act as an essential lubricant at subduction zones, helping to make plate tectonics possible.

The global thermostat

If it were not for Earth's large size, significant internal heat, thin and brittle crust, and upper mantle, plate tectonics may not have existed at all. And neither would we.

Venus is almost the size of Earth but lacks liquid water. Mars is much smaller than Earth and thus apparently has a thicker crust. Neither has active plate tectonics today. And that may help explain why they don't have life, either.

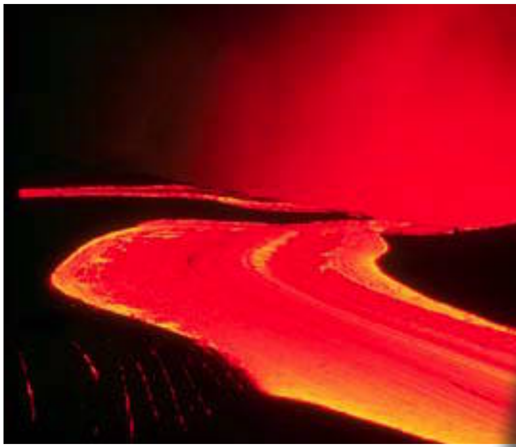
More than anything else, the combination of plate tectonics and active weather maintains a climate suitable for terrestrial life. Plate tectonics prevents carbon dioxide from building up too high and turning the biosphere into a global barbecue, as on Venus.

Carbon dioxide in the air dissolves in rainwater. The water is slightly acidic (carbonic acid), so it reacts chemically with the rock on which it falls. Electrically charged bicarbonate ions, liberated from minerals in surface rocks, ride streams into the sea.

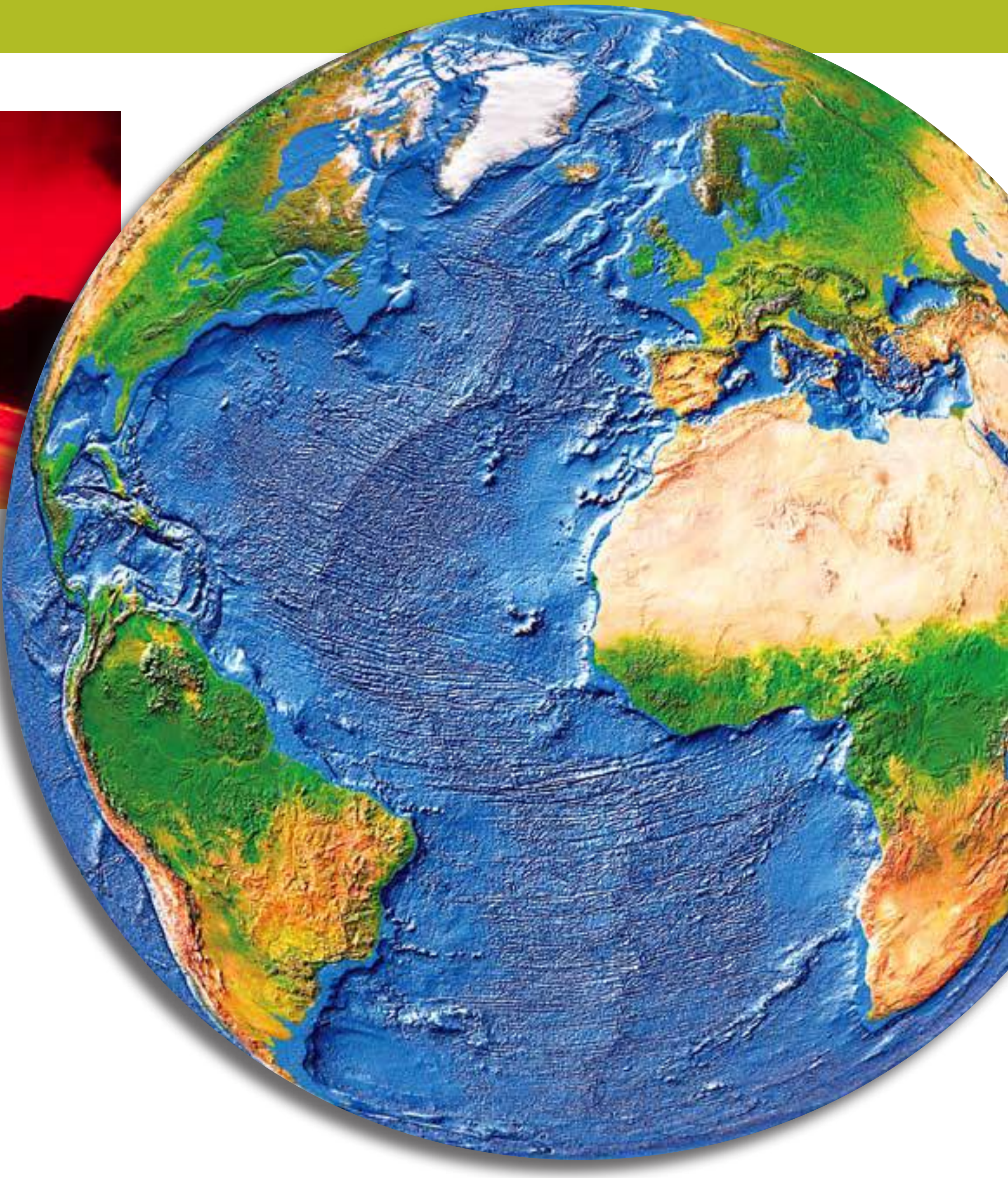
In the ocean, organisms use the bicarbonate ions to build stable shells and other body parts. When the organisms die, the carbonate sinks to the seafloor and eventually becomes carbonate rock, like limestone.

Were carbon storage on the seafloor the end of the story, Earth's atmosphere would have lost most of its carbon dioxide long ago. Lacking this greenhouse gas, the planet would evolve into a frozen world marginally suitable for life.

Jonathan I. Lunine *is a physicist and planetary scientist at the University of Arizona. His research interests include star evolution, planet formation, and the chemical basis for the origin of life in the solar system.*



▲ **ON HAWAII'S KILAUEA VOLCANO, a river of lava flows toward the sea. Eruptions release vast amounts of carbon dioxide, a potent greenhouse gas that helps to prevent Earth from becoming a planetary popsicle.** USGS/HAWAII VOLCANO OBSERVATORY



▲ **EARTH'S INTERNAL HEAT, moderate diameter, and thin, brittle outer crust initiated plate tectonics early in the planet's history. Plate motions and active weather help maintain global temperatures within a relatively narrow and stable range. This image, based on NASA data, highlights the mid-Atlantic Ridge, the boundary where the North American and European plates spread part.** NASA EARTH OBSERVATORY/FRANCIS REDDY/*ASTRONOMY*: ROEN KELLY

Instead, plate tectonics eventually returns carbon dioxide to the atmosphere. This occurs after carbonate rock on the seafloor rides the plates into subduction zones.

Eventually, the carbonates reach the mantle. Heating liberates the carbon in the form of carbon dioxide gas. Volcanic eruptions spew the gas into the atmosphere, where it then contributes to greenhouse warming.

The amount of carbon released or stored has changed over Earth's history. At times when plate motions were faster, increased volcanic activity released carbon dioxide at a quicker pace. But when tectonic stresses raised high mountain ranges like the Himalayas, rainwater erosion removed more carbon from the surface environment — at least temporarily — and cooled the climate.

Delicate balance

Feedbacks in the system are ultimately what maintains Earth as the Goldilocks planet — not too hot, not too cold, but just right. When the climate cools, less water evaporates from the surface. The result is less rain and, therefore, less erosion and less carbon storage. At the same time, plate tectonics still pumps additional carbon dioxide into the atmosphere. The net effect is to raise the surface temperature.

The opposite is also true: When the climate is warm, it rains more. As the erosion rate rises, carbon storage increases and cools the climate. Earth's global climate swings up and down, but it never goes completely out of control, as perhaps it did on Venus.

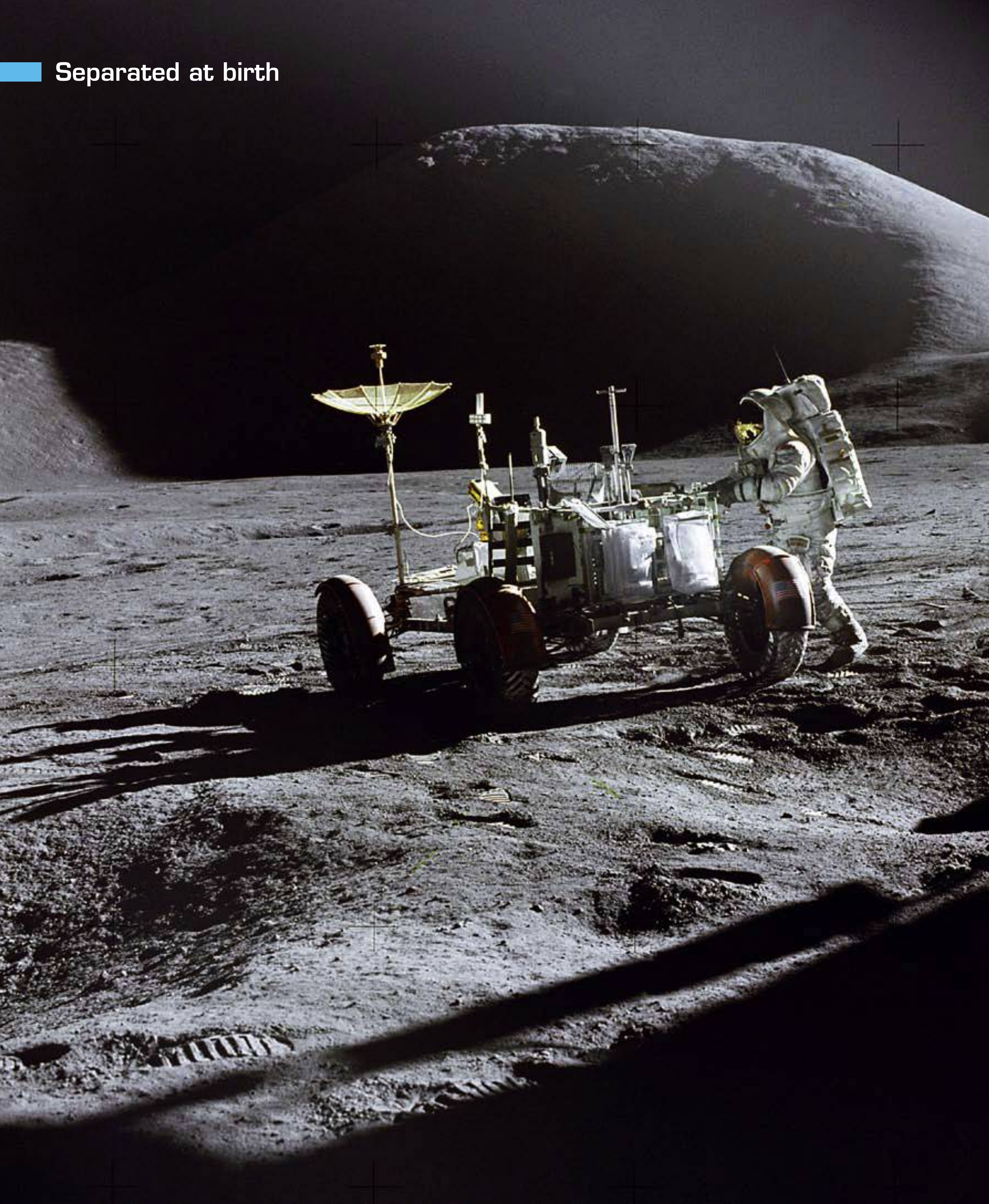
No surprise: Venus lacks both plate tectonics and a water cycle. No rainfall is possible to scrub the massive amounts of carbon dioxide out of its super-greenhouse atmosphere. Mars has no plate tectonics, and hence any carbon dioxide locked up in carbonates or similar compounds is trapped that way forever. Thus, Mars cannot develop a greenhouse-warmed climate.

Geologic evidence suggests that Mars was once warmer and wetter. Today, we observe, it's cold and dry with a tenuous atmosphere. Might it be so today if the Red Planet had plate tectonics? We may never know.

Our home planet has evolved in the middle way. It neither lost its life-sustaining atmosphere, like Mars did, nor developed a dense carbon-dioxide atmosphere, like broiling Venus. But human activity is beginning to throw this out of balance.

Industry, transportation, and other human activities are pumping greenhouse gases into the atmosphere — too quickly for the climate thermostat to compensate. In a century, atmospheric carbon dioxide levels could double.

The climate changes wrought by the enhanced greenhouse effect will be dramatic to humans, but relatively minor compared to past excursions on geologic time scales. Yet humans have the distinction of being not just the only known life-form in the solar system, but also the only one rapidly altering its own environment on a planetary scale. ◘



HUMANS LANDED on the Moon 6 times between 1969 and 1972. Here, astronaut James Irwin works on the lunar rover during the first excursion of the Apollo 15 mission. Mount Hadley looms in the background. NASA

Earth's battered companion

Our knowledge of the Moon remains an intriguing blend of established fact, promising theory, and impenetrable mystery.

by Peter Schultz

The Moon got to me a long time ago. It happened in third grade, when I first glimpsed it through a small telescope. What I saw wasn't a photograph or some imaginary, science-fiction landscape, but real moonlight falling on my eye.

The mysterious dark plains, called maria, and pockmarked highlands became a refuge far beyond the lights of suburban Chicago. With each change in lunar phase, features on the Moon's surface also changed. In sixth grade, I tried to model the Moon from clay. I used the head of a nail to make the craters, but they didn't look right. I finally stumbled on a solution: Use flat-headed nails for the flat-floored craters like Alphonsus, and finishing nails for the fresh, deep craters. Then, the craters looked like those through my telescope.

Reconstructing the lunar landscape made me wonder how nature really did it. At that time, in 1954, popular accounts attributed craters to both volcanic eruptions and collisions. Remember, this was a time when humans had seen only half of its face. The Moon's farside wasn't revealed until 1959, when the Soviet Union's Luna 3 spacecraft returned the first views. Astronauts saw the farside for themselves in 1968, a year before the first lunar landing.

Within the coming 5 years, the next generation of third graders (and lunar scientists) will discover a new Moon. A flotilla of space probes will look at — and beneath — the lunar surface. And not long thereafter, humans once again may set foot on our satellite.

Why should we go back? Scientists have two main objectives. First, it serves the broader vision of sending humans to Mars. Second, the Moon remains a deep mystery. The first age of lunar exploration, which ended 35 years ago, left many questions unresolved. Chief among those: What were the key events that shaped the Moon, and when, exactly, did they occur?

Separated at birth

Most researchers believe a Mars-sized body slammed into Earth soon after our planet

EARTH RISES above the Moon's north pole as Japan's Selene spacecraft flies above in this November 7, 2007, image. The Sun's low elevation at the Moon's poles always throws these regions into stark relief. JAXA/NHK

formed. The Moon then probably developed from the ring of vapor, melted rock, and debris left over from this enormous collision. Mercury and the asteroid Vesta retain scars of similarly huge collisions that nearly destroyed them. While this theory makes sense, and the amounts of trace elements found in lunar rocks supports it, scientists likely will need evidence from the oldest lunar materials to prove it.

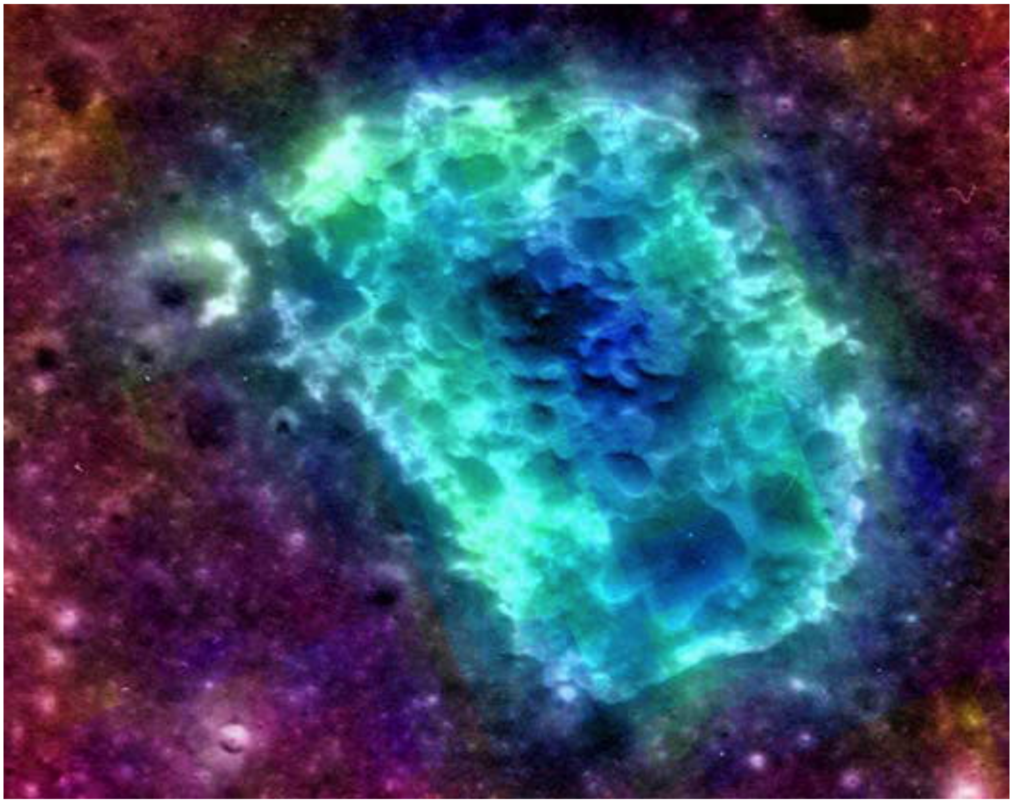
And don't forget: Consensus does not make a theory true. Perhaps Earth adopted a wayward Moon instead. Born elsewhere in the inner solar system, the Moon might have been captured through tidal interactions. Such a suggestion, once thought improbable, could work if Earth had more than one satellite at the time. If so, what happened to those other companions? Perhaps they slammed into Earth, where their record would have been destroyed long ago. Or maybe they produced some of the Moon's ancient impact basins.

From when the lunar crust cooled, the Moon's history divides into five chapters, or "periods." The first chapter describes the Moon's formation and covers its first 500 million years; the last began before the explosion of life on Earth some 540 million years ago. Major events mark the beginning of each chapter.

The Pre-Nectarian Period (the first chapter) dates from so long ago that we see only heavily degraded impact basins remaining from it. The Nectarian Period spans a relatively short time, perhaps only 150 million years. During this period, an onslaught of large bodies produced many impact basins, including Nectaris and Humorum. Planetary scientists call this time the Late Heavy Bombardment, when it appears the cratering rate throughout the inner solar system increased suddenly and dramatically.

The Imbrian Period covers the era following the creation of the last major nearside basin, the Imbrium impact basin. Massive lava flows poured across the Moon's nearside like chocolate syrup then. Oddly enough, only small patches of the farside experienced lava flows.

The Eratosthenian Period dates from after this age of volcanism to before space weathering

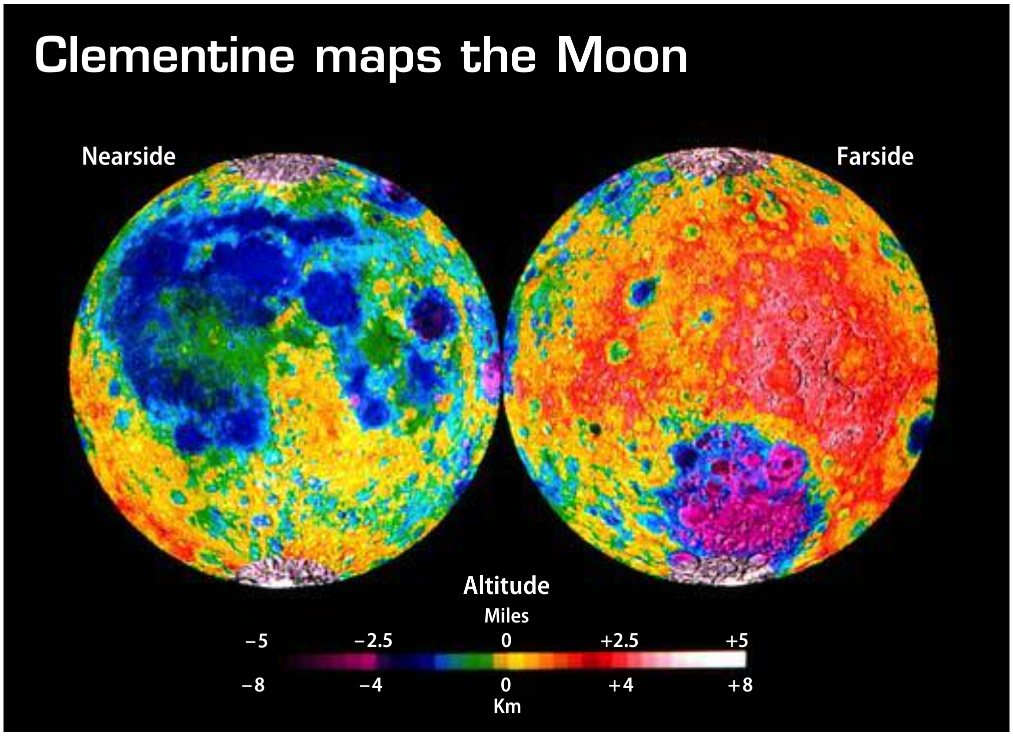


▲ **A BURST OF GAS** from the Moon's interior likely cleared away lunar regolith at this structure, called Ina, within the past 10 million years. This false-color image taken during the Apollo 15 mission reveals freshly exposed titanium basalts as blue and relatively unweathered soils as green. P. SCHULTZ (BROWN UNIVERSITY), ET AL./NASA (from meteorites, the solar wind, and cosmic rays) erased the bright rays from large craters. Large craters that still preserve their bright rays define the last chapter, the Copernican Period.

Those five periods don't tell the whole story, however. Lunar scientists still debate exactly when each period ends and the next begins. Good evidence suggests lava continued to erupt into the Copernican Period, around 1 billion years ago. With loads of new data from upcoming space probes, scientists likely will subdivide each period into smaller epochs and eras, which might even be linked with Earth's history.

For Earth, sudden changes in the evolution of life mark major transitions in time. Most of them occurred during the last 100 million years. For the Moon, almost everything happened during its first 800 million years, and remains well-preserved after another 3.8 billion years.

Major impacts, like the one that gouged out the crater Copernicus, or widespread volcanic activity will continue to delineate these transitions. But imagine if we could link a specific lunar crater with debris trapped in sediments on Earth. The opposite might happen, too, where we find debris on the Moon that was ejected from a dated terrestrial crater.



▲ THE MOON'S TWO SIDES appear distinctly different in this topographic map made from data returned by the Clementine spacecraft's laser altimeter. The nearside features several large, deep basins, while the farside has few. However, the farside does feature the huge South Pole-Aitken basin (bottom), which spans 1,550 miles (2,500 km). BMDO/NRL/LLNL/LPI/UA

Dead or alive?

For the most part, the Moon is now geologically dead. Still, things are happening. Collisions with small pieces of interplanetary debris generate intense heat. Both amateur and professional astronomers regularly report seeing brief flashes from these impacts.

IMAGINE IF WE
link a lunar crater with debris trapped in sediments on Earth.

Not long ago, researchers thought such lunar impacts would produce flashes lasting only a few thousandths of a second — far too brief to be seen from Earth except through the largest telescopes. As a result, scientists often ignored or totally dismissed reports about observed changes on the Moon, especially after a long history of false alarms.

Continuous lunar monitoring now reveals that objects weighing a couple of pounds (1 kilogram) not only strike the Moon's surface every month, but also can be seen from Earth with a 12-inch telescope. Some flashes peak as bright as 7th magnitude. This makes them easily visible through binoculars, but they last less than half a second — the blink of an eye.

Astronomers at NASA's Marshall Space Flight Center in Huntsville, Alabama, now monitor lunar impacts to understand what hazard this debris could pose to future lunar bases. My students and I have performed laboratory experiments at NASA's Ames Vertical Gun Range to study such high-speed impacts. Our studies help calibrate the connection between an impact's energy and the light it generates.

Impact flashes aren't the only changes happening on the Moon today. Scientists have found some small depressions swept clean of lunar regolith — the impact-battered dust that forms the Moon's "soil." The exposed rocky surfaces of these depressions, which were not created by recent impacts, show little impact weathering. It appears sudden outbursts of gas (think of them as lunar burps), removed regolith up to 20 feet (6 meters) thick.

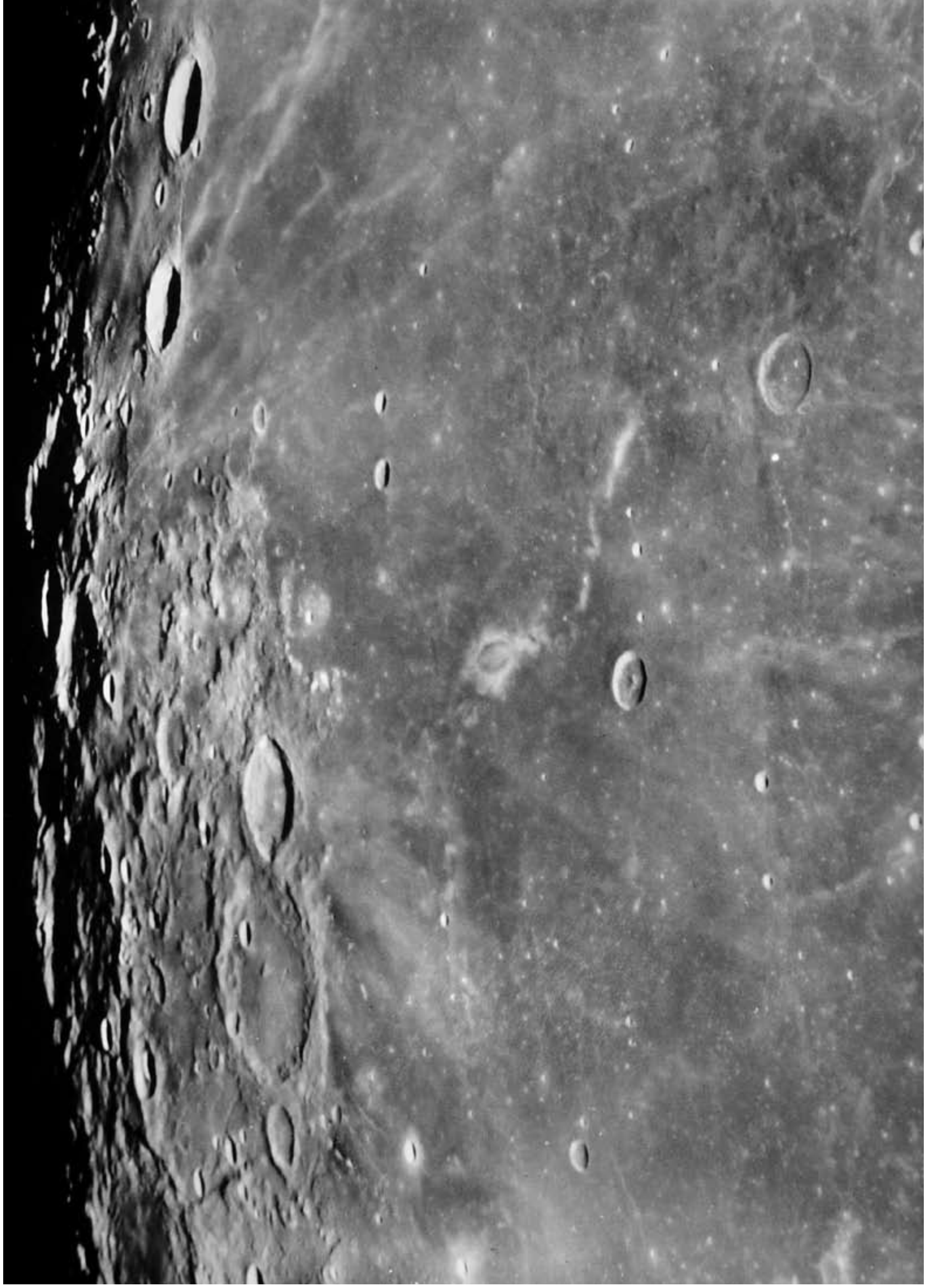
Because lava last flowed on the Moon more than a billion years ago, such gas must originate deep inside of it. Instruments on the Apollo missions, and later on Lunar Prospector, measured traces of gas still escaping from young lunar craters, including Aristarchus — the Moon's brightest feature. Some radioactive elements in this gas decay so quickly, they must have been released within the previous days or months. We may be able to watch this happen when we return for closer looks.

▲ A BRIGHT FLASH marks the spot where a meteoroid smashed into the Moon May 2, 2006. The space rock measured about 10 inches (25cm) across and packed a wallop equivalent to 4 tons of TNT.
HEATHER McNAMARA/DANIELLE MOSER/MSFC

Surprises to come

Although the Apollo exploration program ended 35 years ago, lunar research has not. The rock samples returned by astronauts keep revealing new clues about the time when the Moon had a magma ocean 300 to 600 miles (500 to 1,000 kilometers) thick. Denser minerals sank into the interior while lighter minerals floated to the surface. The lighter stuff formed the light-colored, cratered highlands.

Although the Apollo astronauts sampled several different parts of the Moon, those aren't



▲ **REINER GAMMA appears as a swirly pattern of bright material in western Oceanus Procellarum. This and similar features often appear at the antipodes of major impact sites.** CONSOLIDATED LUNAR ATLAS/UA/LPL

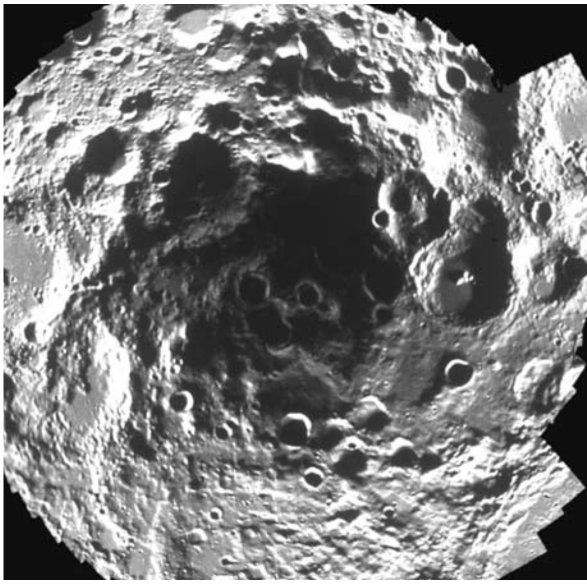
the only lunar samples we have. Scientists have discovered that some meteorites on Earth came from the Moon. Launched by impacts into orbits around the Sun, these meteorites arrived here about 500,000 years later.

Lunar meteorites are like a closed box at an auction: We take what we get without any idea where the contents came from. In contrast, the Apollo astronauts meticulously kept track of their samples, so we know their geologic context. Examining the Apollo rocks helps us identify and make sense of the random collection of lunar meteorites, which now number more than 30.

__Peter Schultz__ is a professor of geological sciences at Brown University in Providence, Rhode Island.

For example, one meteorite contains evidence that it came from a region rich in KREEP — an acronym that stands for levels of potassium (K), rare earth elements (REE), and phosphorus (P) much higher than average lunar crust. KREEP occurs in patches concentrated primarily on the Moon's nearside. Some meteorites are a mishmash of compressed debris, called breccia, created by ancient impacts.

Studies of small rock and mineral fragments trapped inside one lunar meteorite reveal it likely came from a region of enhanced KREEP that may predate the Imbrium basin, which formed 3.85 billion years ago. In this case, NASA's late-1990s Lunar Prospector spacecraft provided the geologic context by mapping elements, such as thorium, linked to the formation of KREEP-rich rocks.



▲ **THE MOON'S SOUTH POLE harbors many deep craters that remain perpetually in shadow. Scientists think such "cold traps" could protect major sources of water ice.** BMDO/NRL/LLNL/LPI/UA

The results raised intriguing questions about when the Late Heavy Bombardment happened, and even when Mare Imbrium formed. To solve these mysteries, scientists need more samples and to know exactly where they came from.

These aren't the only remaining mysteries about the Moon. Based on measurements made by the Clementine and Lunar Prospector missions, water ice may lurk in permanently shadowed regions at the Moon's poles. These areas act as cold traps, where temperatures stay a constant –380° Fahrenheit (–230° Celsius).

This water ice may have built up gradually from water molecules released when cometary debris hit the Moon and migrated to places where the Sun doesn't shine. Over billions of years, even individual molecules add up. Estimates suggest less than 1 percent of lunar regolith contains ice. But at the poles, where many craters are permanently shadowed, humans might be able to tap the ice. Later this year, NASA's LCROSS mission will slam into one of these areas, blast out what's below, and analyze the debris cloud as it rises into sunlight.

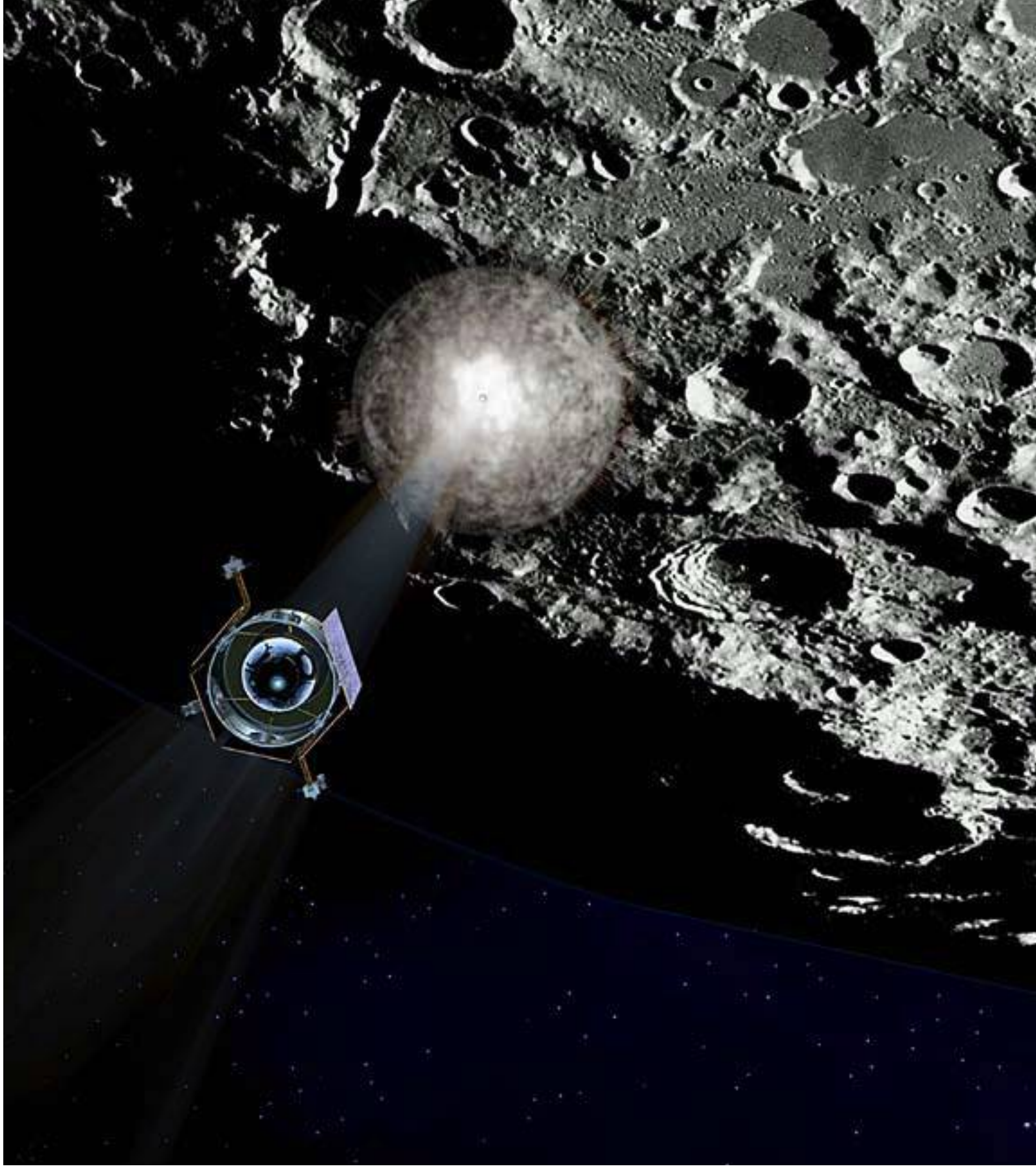
A tale of swirls

Another mystery may relate more to heat than cold. Lunar scientists observe odd swirly patterns draped across both sides of the Moon. Under certain lighting conditions, they appear to float above the lunar surface because they

STATISTICS: Moon vs. Earth

	Moon	Earth comparison
Mass	0.1620 trillion trillion pounds	1.23% of Earth's
Diameter	2,160 miles	27.3% of Earth's
Density	3.35 grams/cc	60.7% of Earth's
Weight of 150-lb person	25 pounds	16.5% of Earth's
Distance from Earth	239,000 miles	—
Orbital period	27.322 days	—
Length of day	708.7 hours	29.5 times Earth's

Mass: Total mass (1 trillion = 10^{12}); **Diameter:** Equatorial diameter; **Density:** Average density in grams per cubic centimeter (water = 1); **Distance from Earth:** Average distance; **Orbital period:** Sidereal period; **Length of day:** Average time between successive noons; **Earth comparison:** Ratio of the Moon's to Earth's value.



▲ **LCROSS SMASHES into the Moon's south polar region in this artist's concept. The impact later this year will raise a plume of material that a shepherding spacecraft and scientists on Earth will analyze for signs of water ice and vapor.** NASA

scatter more light than their surroundings at high-phase angles (when the Sun shines from directly behind).

Although the most famous example is the Reiner Gamma Formation in western Oceanus Procellarum, the biggest display lies on the Moon's farside. Many of the swirls correlate with trapped magnetic fields. Contrary to some studies, however, not all of this terrain has a strong magnetic field. And not all of it lies at the antipodes — the spots on the surface exactly opposite — of large impact basins.

Scientists have developed three competing hypotheses to explain these swirls. The first says they result from the convergence at the antipode of material moved there by an impact that formed a basin. The second proposes they are recent high-speed imprints from the densest portions of a comet, which scoured and heated the surface's top layer. The third idea states they come about from interactions with secondary impacts or ejecta from more recent impacts.

All three hypotheses have profound implications for lunar scientists. If the swirls arise from antipodal convergence, then ancient magnetic fields trapped below the surface shield the surface from solar protons and space-weathering effects. If caused by a comet impact or secondary ejecta, the swirls indicate a geologically recent collision, perhaps one that could be tied to an event on Earth. High-resolution spectroscopy of both the light and dark components of the swirls may help resolve this debate.

WATER ICE MAY lurk in permanently shadowed regions at the Moon's poles.

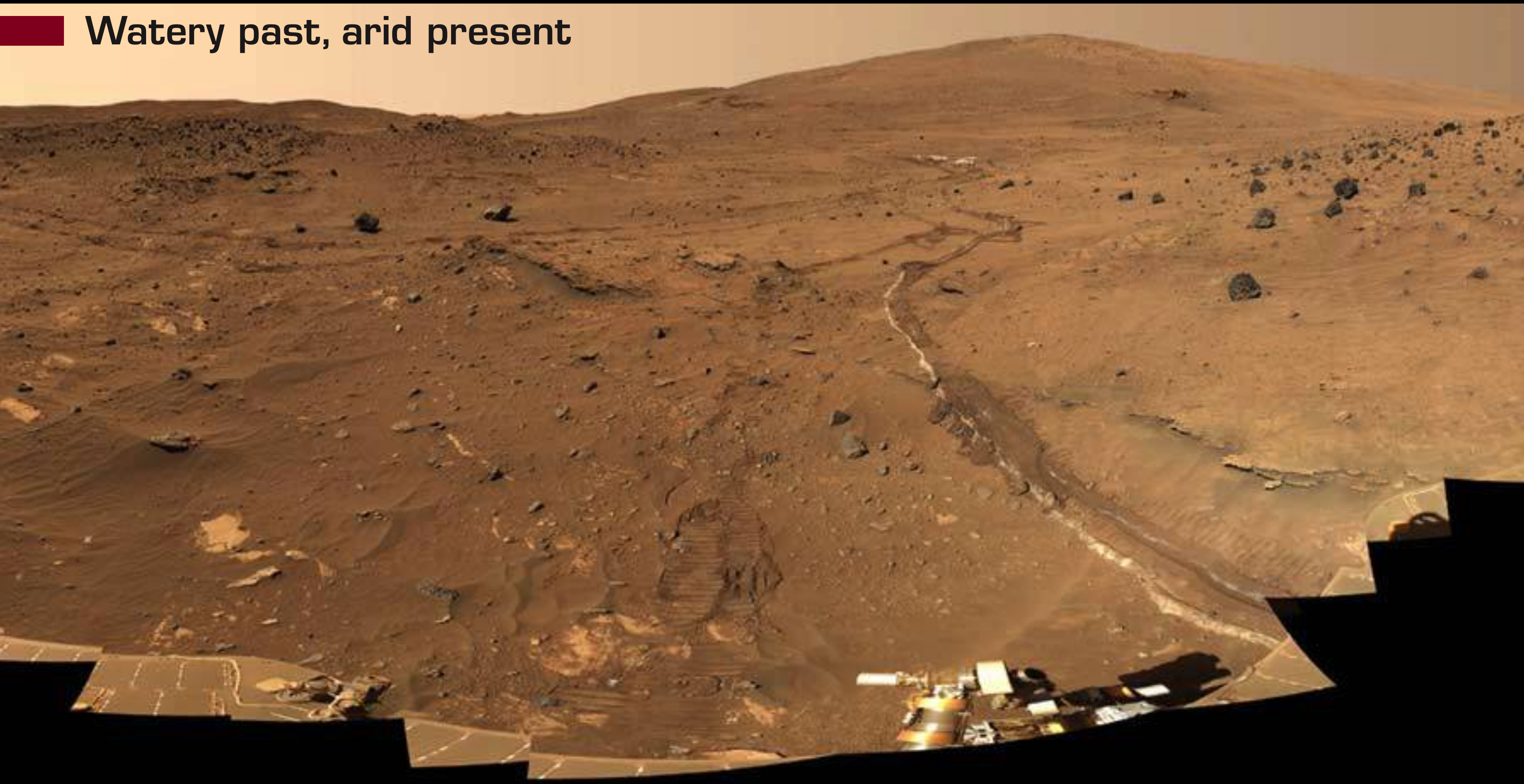
Witness to home

Events on Earth get erased rapidly on a geological timescale. That's one reason scientists look to the Moon for clues about our past. For example, the Moon might hold signs of impact showers. Astronomers have discovered families of asteroids whose orbits all meet at specific moments in time. The best guess: Each family represents the breakup of an asteroid 60 miles (100 km) across or bigger.

One such event may have sent dust laden with helium-3 spiraling toward the inner solar system, and researchers have found this cosmic tracer in deep-sea sediments. On a cosmic time scale, this happened essentially yesterday — in the last 12 million years.

Have other asteroid breakups also resulted in sudden rains of debris? The Moon might record this secret. Perhaps the Chicxulub impact, which scientists believe wiped out the dinosaurs 65 million years ago, was not a lone marauder. It's even possible the Moon will show that impact catastrophes occur in cycles. If so, we might be able to connect those cosmic events with sudden extinctions or expansions of life on Earth.

As a new age of lunar exploration begins, I still feel like I did when I first looked through a telescope. Seeing the Moon through a spacecraft's eye or solving longstanding mysteries won't take away this excitement. The Moon is family, whether born or adopted. And hidden in its rocks are stories about our earliest years — and perhaps our future. ◘



Will the real Mars please stand up?

“Mars beckons,” said the late astronomer Carl Sagan. With that, he captured centuries of fascination with the Red Planet in just two words. Earthlings have conceptualized Mars in many different ways, but we are now in the midst of the golden age of robotic exploration of the fourth planet from the Sun.

Scientists currently use three orbiters and two rovers, and the Phoenix lander is on the surface. But do we know the real Mars yet?

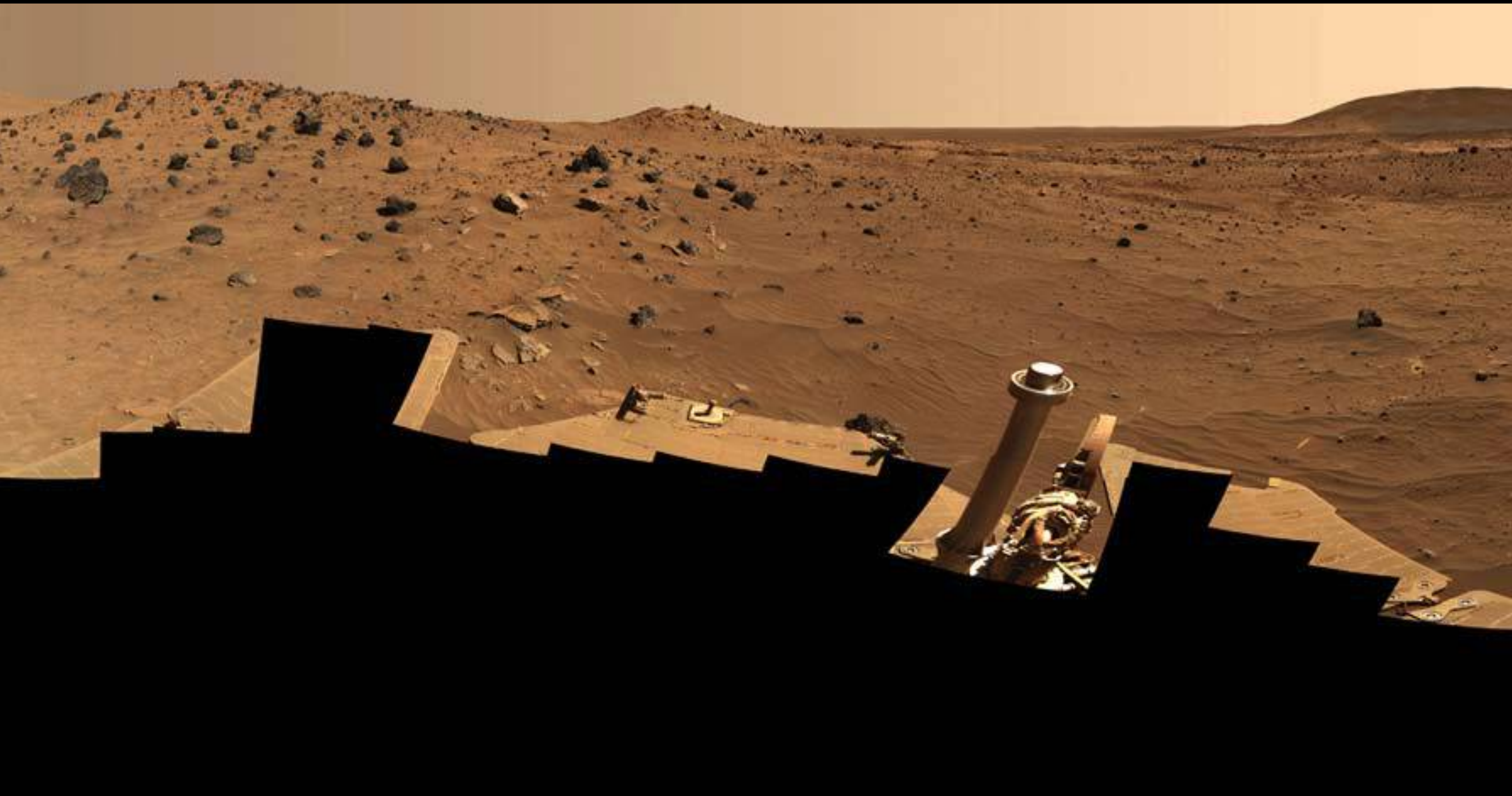
Astronomers have long known Mars resembles Earth in several ways. It has a day just 39.6 minutes longer than ours. Its spin axis tilts 25.19° (Earth tilts 23.45°), so both planets have distinct seasons and bright winter polar caps that shrink in the summer. Mars’ atmosphere also contains clouds and changing weather.

Not like Earth

The first close-up images of Mars from the unmanned Mariner spacecraft flybys in the late 1960s revealed the Red Planet's heavily-cratered highlands at scales of kilometers. The spacecraft measured a low-density atmosphere of mostly carbon dioxide (CO_2), with a surface pressure less than 1 percent that of Earth.

Those early results led many astronomers to abandon the idea of an earthlike Mars. Rather, they described the planet as more like the Moon with a thin atmosphere. But even from those early images, researchers recognized eroded and filled-in craters. Mars, therefore, must have had a different geologic history than the Moon.

In 2000, Mars Global Surveyor discovered that many old craters held layered sedimentary rocks and minerals containing water. Such sites have become prime candidates for future rovers. So, these initially disappointing landforms are now of great interest.



THIS 360° VIEW, called the McMurdo panorama, comes from NASA's Mars Exploration Rover Spirit. It is the highest-resolution view of Mars acquired from either rover. Many dark, porous-textured volcanic rocks sit around the rover. Two rocks to the right of center, brighter and smoother-looking in this image, are martian meteorites. NASA/JPL/CORNELL

Recent findings show the Red Planet to be unlike Earth and the Moon — In fact, it's somewhere in-between.

by Alfred McEwen

The Mariner 9 and Viking orbiters of the 1970s provided a global view of Mars, revealing giant volcanos, canyons, and channels; layered polar deposits; and dynamic atmospheric phenomena. But the Viking landers found the surface to be dry and devoid of organic material at two locations, so the prospects for life-as-we-know-it on Mars dimmed.

A little like the Moon

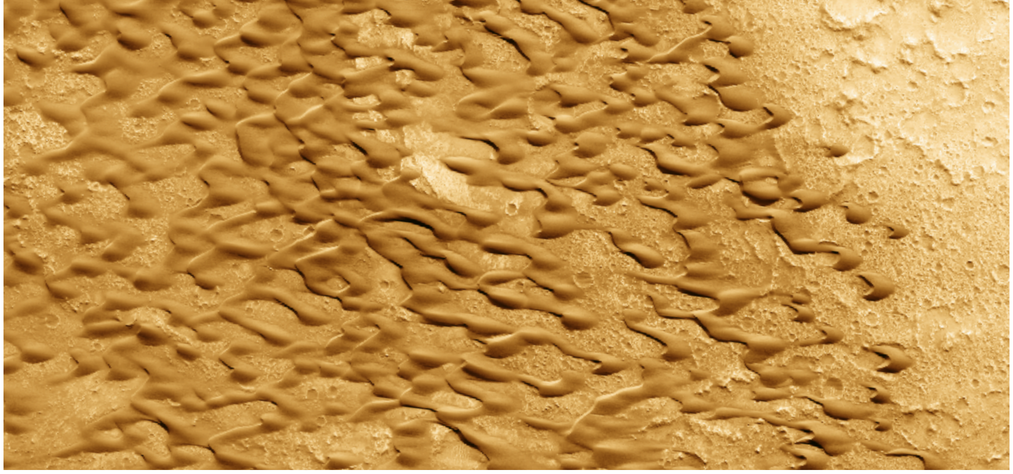
Mars resembles the Moon in some ways and Earth in others. Like the Moon, many large impact craters dot Mars' surface. On the other hand, tectonics and erosion have reshaped Earth's surface almost completely. Basaltic flood lavas fill the lowlands of Mars and the Moon, but that's also true of Earth (i.e., the ocean basins). Neither the Moon nor Mars has an active core creating a magnetic field, although Mars' crust has remnant magnetic anomalies.

The Moon's highland crust is rich in light minerals like plagioclase, which floated to the top of the ancient ocean of molten rock. Subsequent processes almost completely recycled and altered Earth's primordial crust.

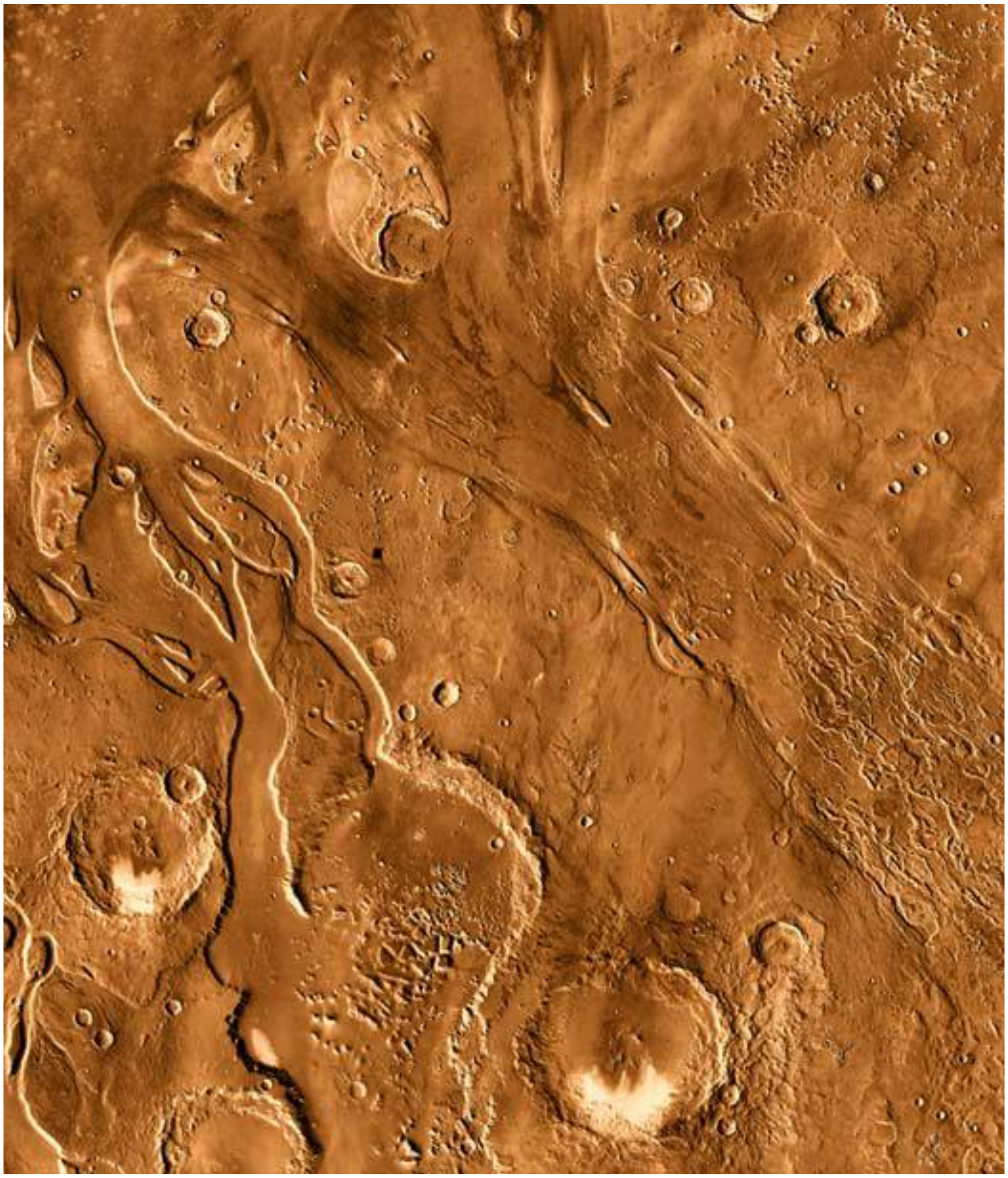
The highland crust is the subject of active debates. If the entire highlands are as complicated as the Columbia Hills, which the Spirit rover explored, the debates will not end soon.

Mars has dry river channels, water-carved valley networks, and evidence for glaciers similar to Earth. Such features are impossible on the dry Moon. But martian water- and ice-carved landscapes have not reached maturity. "Mature" means the features reach an equilibrium that

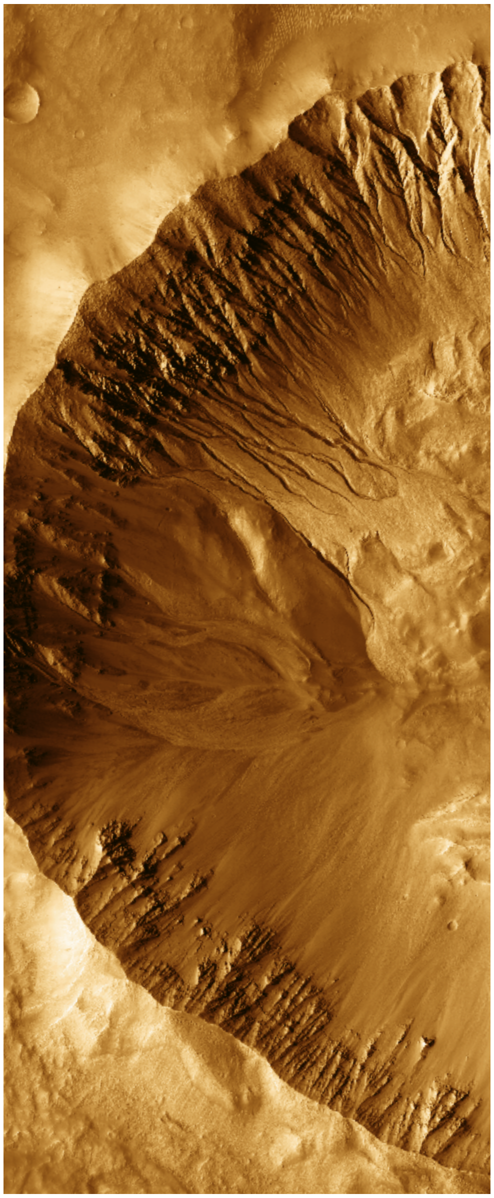
Alfred McEwen *is the principal investigator for the Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment.*



▲ **HERSCHEL CRATER** is a roughly 180-mile-wide (300 km) impact basin in Mars' southern highlands. A field of dark-toned barchan sand-dunes sits on the crater floor. Such dunes form by winds that blow mostly in one direction. Those dunes suggest the dominant wind blows approximately north to south. MRO's HiRISE took this image March 7, 2007. North is up in this image. NASA/JPL/UNIV. OF ARIZONA



▲ **CHANNELS SCOURED** by ancient floods appear in this orbital view from Mars Odyssey's Thermal Emission Imaging System (THEMIS). The channels are billions of years old and likely have been affected by multiple processes over time. Here, two channels, Tiu Vallis on the left and Ares Vallis on the right, flow northward from the highlands. The stark difference between today's cold, dry Mars and its potentially wet past tells scientists the martian climate underwent great changes. NASA/JPL-CALTECH/ASU



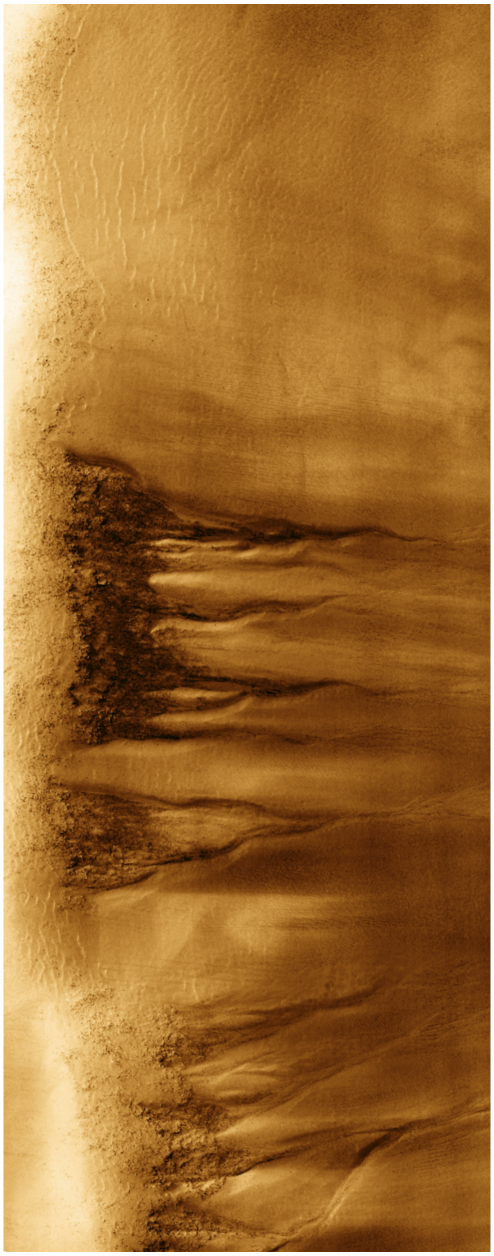
▲ **GORGONUM CHAOS** is a large martian basin featuring gullies that provide evidence of fluid flow. Of note is the variety of gullies along the crater walls. Gullies scar the north wall, while landslides occur on the south. Many gullies appear to have boulders littered throughout. This suggests fluids, which would preferentially transport smaller particles once found there and leave behind the larger ones.

NASA/JPL/UNIV. OF ARIZONA

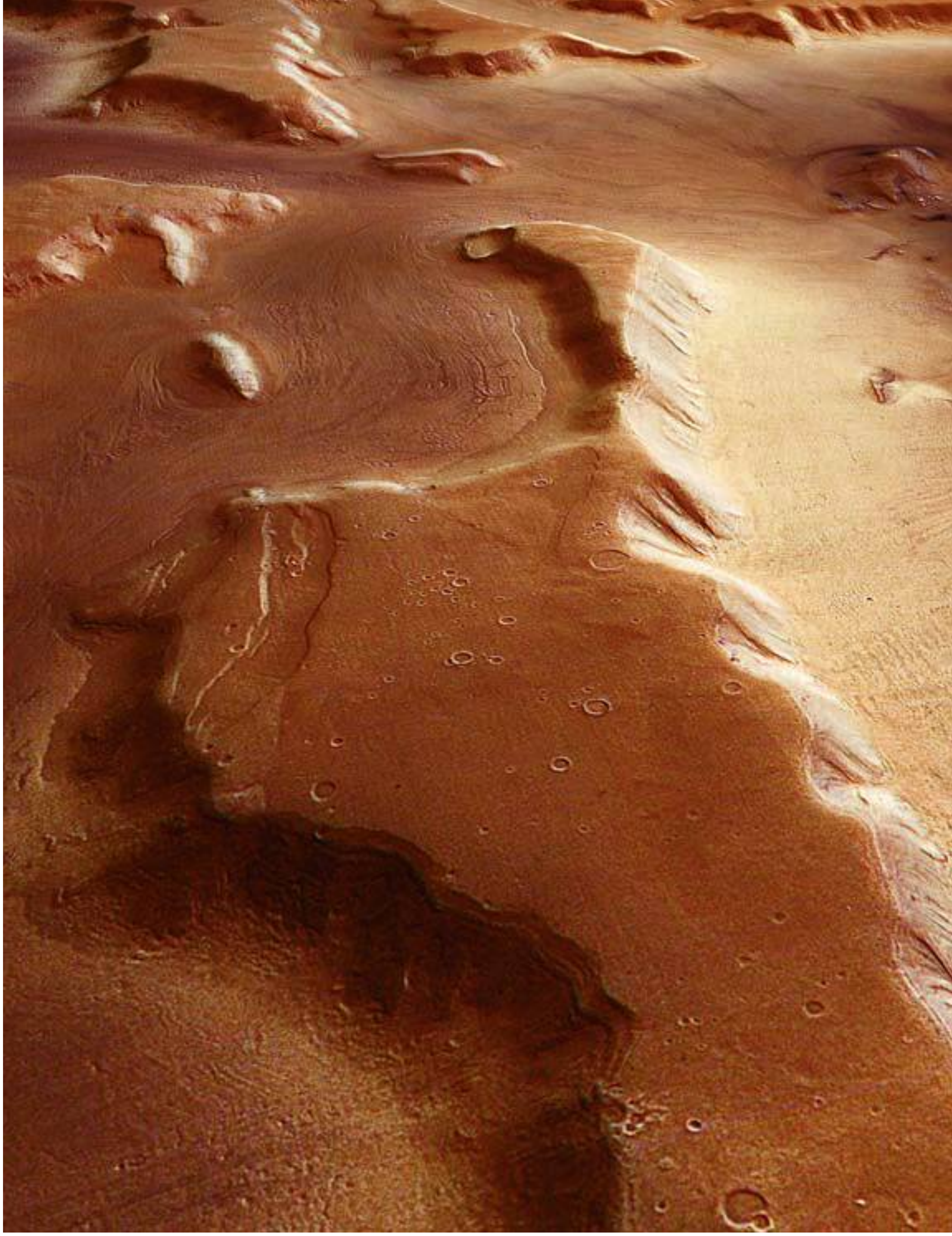
results from many episodes of erosion. So maybe Mars was earthlike for a brief period.

Planet Kieffer

Astronomers can't adequately describe Mars as some combination of Earth and the Moon. I think of it as "Planet Kieffer," a term I named for Hugh Kieffer, planetary scientist now retired from the United States Geological Survey, who urged his colleagues to "think like martians." Processes and landforms exist on Mars that are absent on both Earth and the Moon.



▲ **AT ALICANTE,** **north of Victoria Crater, Opportunity imaged soil where wind produced alternating light and dark streaks. A concentration of dark sand appears on the downwind side of a rock. The High-Resolution Imaging Science Experiment camera on the Mars Reconnaissance Orbiter acquired this view April 18, 2007.** NASA/JPL-CALTECH/UNIV. OF ARIZONA/USGS



▲ **THE DEUTERONILUS MENSAE REGION** **sits on the edge of Arabia Terra and straddles Mars' southern highlands and the northern lowlands. This perspective view shows valleys 2,600 to 3,900 feet (800m to 1,200m) deep. The valleys may have originated from intense flooding by melted water ice. The water then froze quickly and "flowed" down the slopes like a glacier.** ESA/DLR/FU BERLIN (G. NEUKUM)

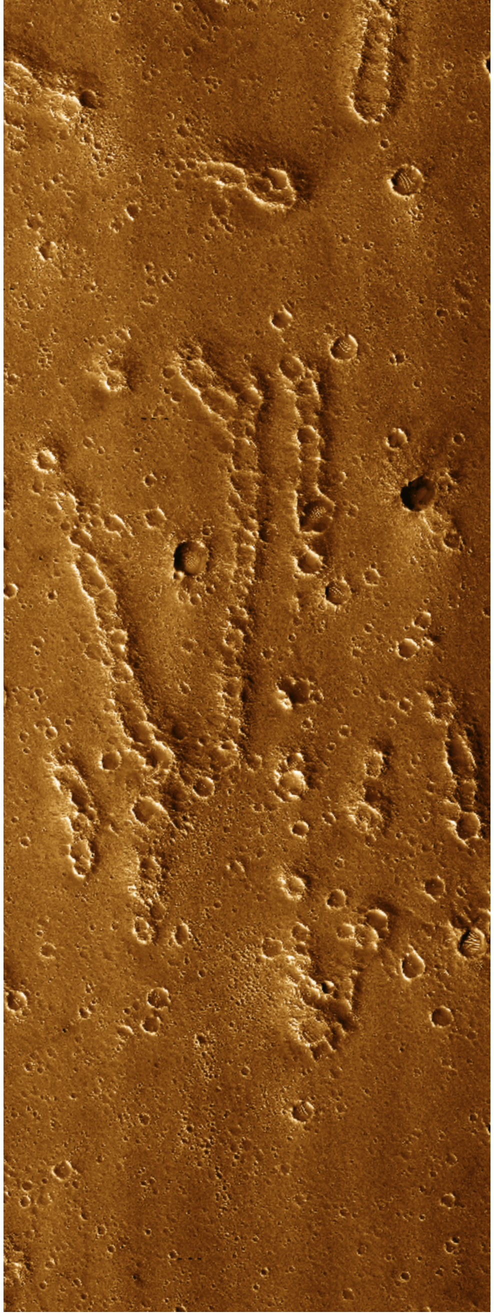
Planet Kieffer resembles several of the outer solar system's large, icy satellites. For example, dark fan-shaped deposits appear on the seasonal CO_2 ice cap in the spring, perhaps due to eruptions of CO_2 similar to the geysers on Neptune's moon Triton. These fans associate with bizarre landforms called "spiders" — systems of channels that appear to flow uphill.

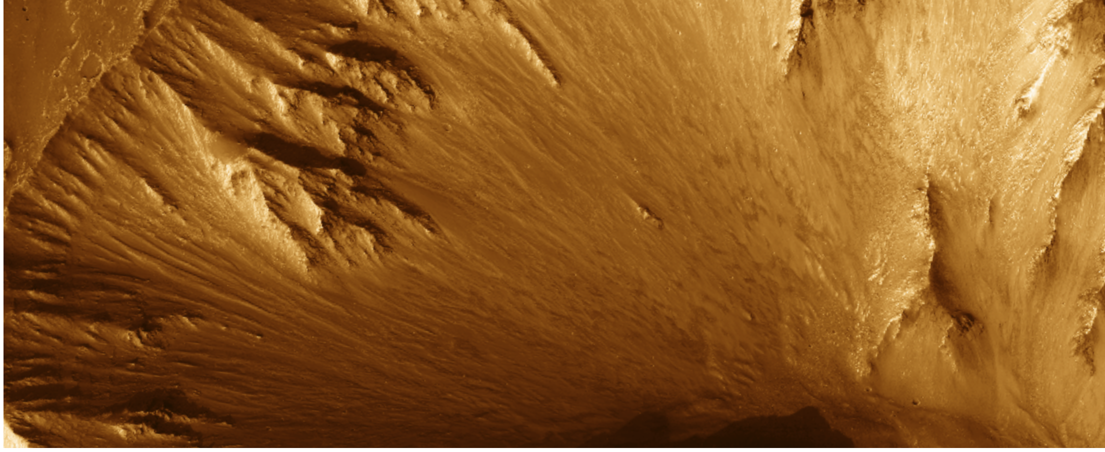
The residual (persisting through summer) south polar ice cap makes a strange, pitted landscape described as "Swiss cheese," formed by CO_2's sublimation and condensation. The icy satellites and dwarf planets of the outer solar system may have equally strange landscapes, but astronomers have not yet imaged them at sufficiently high resolution.

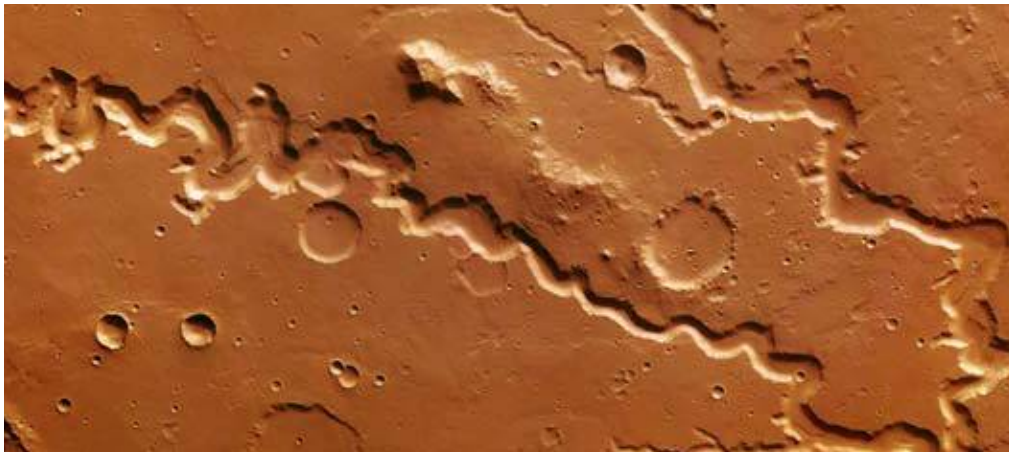
Dusty Mars

Mars is alone in the solar system when it comes to planet-circling dust storms. Deserts on Earth can produce some impressive dust storms, but all are local or regional storms. Such dust storms are common on Mars, and they usually die out after a few days. Sometimes, however, they reinforce each other, spawning new storms, until dust lofted high in the atmosphere obscures almost the entire planet.

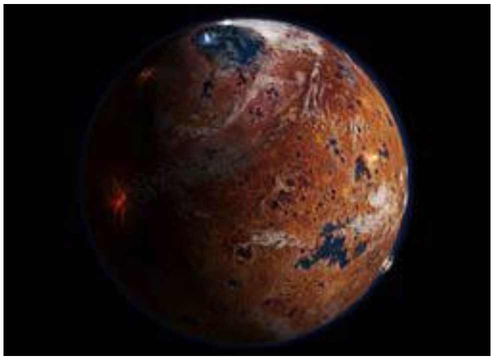
In 1971, Mariner 9 arrived during one of these great storms, and the Viking landers sat through another in 1977. Only one such global event occurred during the decade (5 martian years) of Mars Global Surveyor observations. The most recent dust storm occurred in 2007, endangering the Spirit and Opportunity rovers by blocking the Sun and reducing power to dangerously low levels.



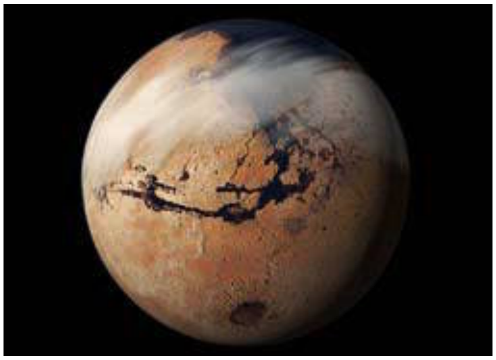




▲ DAO VALLIS IS A CANYON carved into the side of the ancient volcano Hadriaca Patera. A mantling deposit covers the valley wall. Only faint traces of rocky layers — which might be eroded ancient lava flows — are visible. The underlying surface is ancient, but the mantling deposit is young, or it renews itself quickly. NASA/JPL/UNIV. OF ARIZONA



▲ MARS LOOKED DIFFERENT 4 billion years ago in the Noachian period. This computer-simulated image, made using actual martian terrain data, shows the young planet has lakes and erupting volcanos. The large lake at the bottom right is Meridiani Planum, where the Opportunity rover found evidence of such an inner sea. KEES VEENENBOS



▲ THE RED PLANET settled down geologically about 3.5 billion years ago. This computer-generated image shows it still partially covered with water. Chryse Planitia lies at the top. Valles Marineris stretches nearly halfway across the planet. Near the bottom sits Mars' second-largest impact basin, Argyre Planitia. KEES VEENENBOS

Earthly dust eventually gets trapped in bodies of water. On Mars, the dust traps are tall volcanic landforms. Storms loft dust to those heights, where it slowly settles to the ground. Air at those altitudes, however, is too thin to remove dust, especially when rough lava traps it. High-resolution images of tall volcanos like Olympus Mons appear smeared because a thick mantle of dust smooths the terrain.

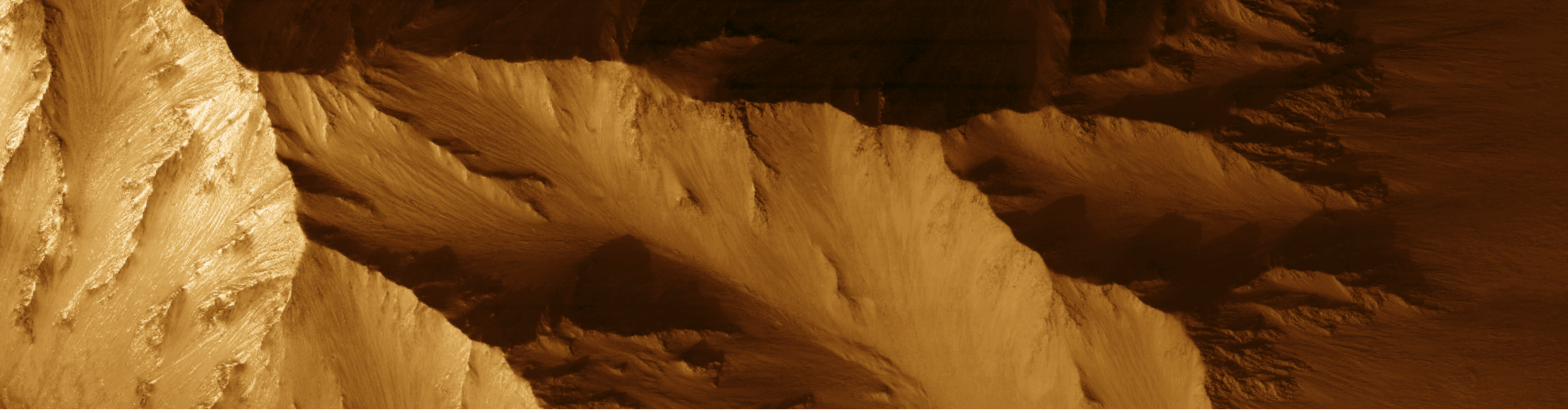
Cratered Mars

Like the Moon, Mars has many impact craters. But when we image them at high resolution, striking differences appear. Recent small impacts into dusty areas blast away the dust and create large dark spots. Instead of single craters, we often see tight clusters of them. This is because the meteorites break apart into multiple fragments as they fly through the atmosphere.

Large craters draw more attention from planetary geologists. Their ejecta (material blasted out at impact) appears to be rich in fluids, perhaps both melted rocks and water. The key difference from the Moon is that Mars' upper crust is rich in water via some combination of ice, deep groundwater, and hydrated minerals. Add a source of energy, and interesting things happen. Craters measuring more than 60 miles (100 km) in diameter should have produced hydrothermal systems that persisted for thousands of years. Some could have supported primitive life.

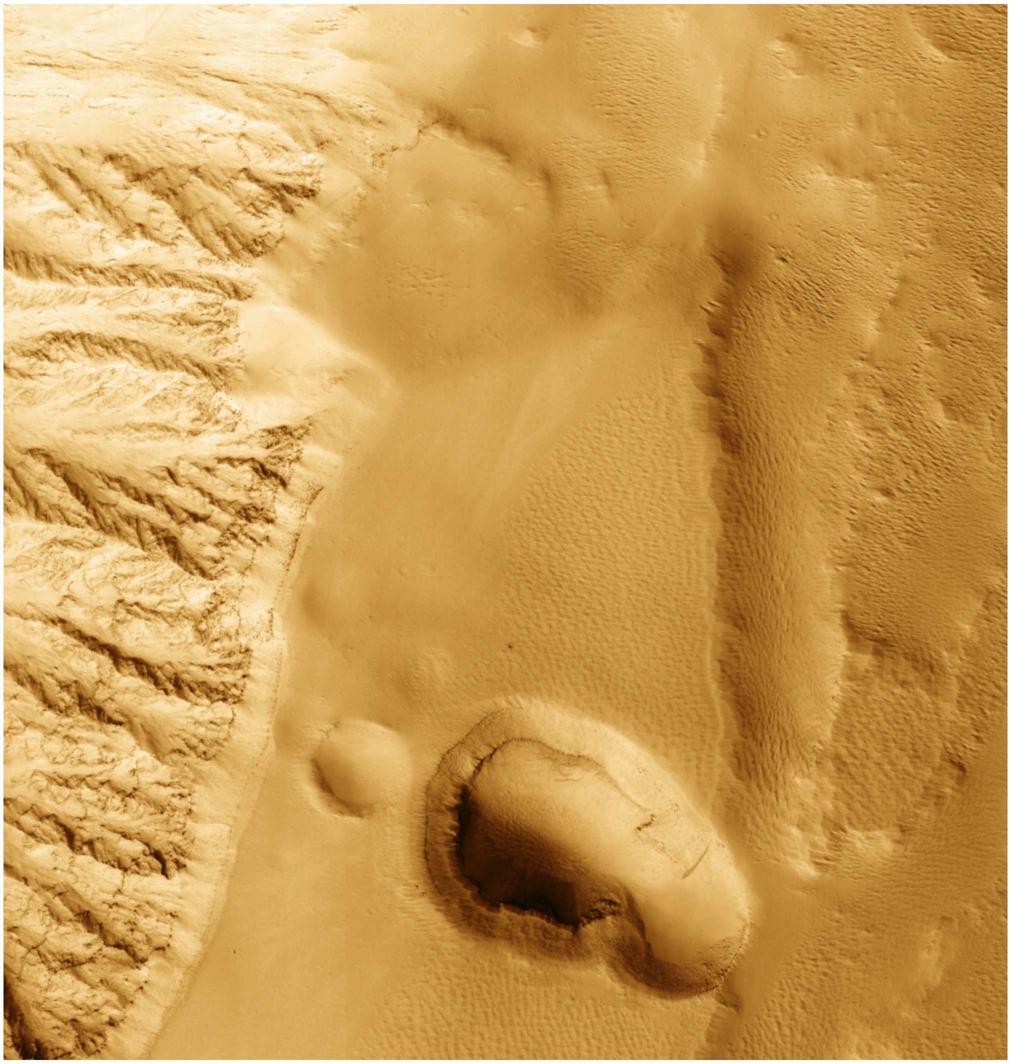
Mars rocks tell their story

Recent Mars missions have clarified the mineral compositions within the planet's crust, which tells the story of Mars' geologic and climatic evolution. Martian meteorites found on Earth are igneous rocks formed by volcanos or



▲ **VALLES MARINERIS** is the largest canyon in the solar system. This HiRISE image captures 31,000 feet (9,500 meters) of vertical relief along the valley's northern wall. A sequence of thin layers appears in the uppermost 3,000 feet (914m). Because Valles Marineris cuts into the side of the Tharsis Volcanic Rise, these layers are probably lava flows. NASA/JPL/UNIV. OF ARIZONA

◄ **NANEDI VALLES,** a roughly 500-mile-long (800 km) valley lies in the region of Xanthe Terra. The section of Nanedi Valles in this image ranges from 0.5 mile to 3 miles (0.8 to 5 km) wide and extends to a maximum depth of about 1,600 feet (500m). Scientists debate whether the valley formed by erosion caused by groundwater outflow, flow of liquid beneath an ice cover, or collapse of the surface in association with liquid flow. ESA/DLR/FU BERLIN (G. NEUKUM)



► **A STEEP SCARP MARKS** the bottom of Olympus Mons, the solar system's largest volcano. This scarp, which runs from upper center to lower left, likely is the result of the volcano collapsing under its own weight. The scarp exposes internal structure, revealing a stack of once deeply buried lava layers. Atop the lava sits a thick layer of volcanic ash or dust carried by dust storms. The pit near the image's center shows the layering extends for some distance up the volcano's flank. NASA/JPL/UNIV. OF ARIZONA

underground sources of molten rock. But the meteorites' age distribution is strange. Most are geologically young, unlike the majority of surface terrains. For a rock to be ejected at speeds greater than Mars' escape velocity requires special conditions. Hard, layered rocks like lavas meet these conditions best, so they are preferentially sent toward Earth.

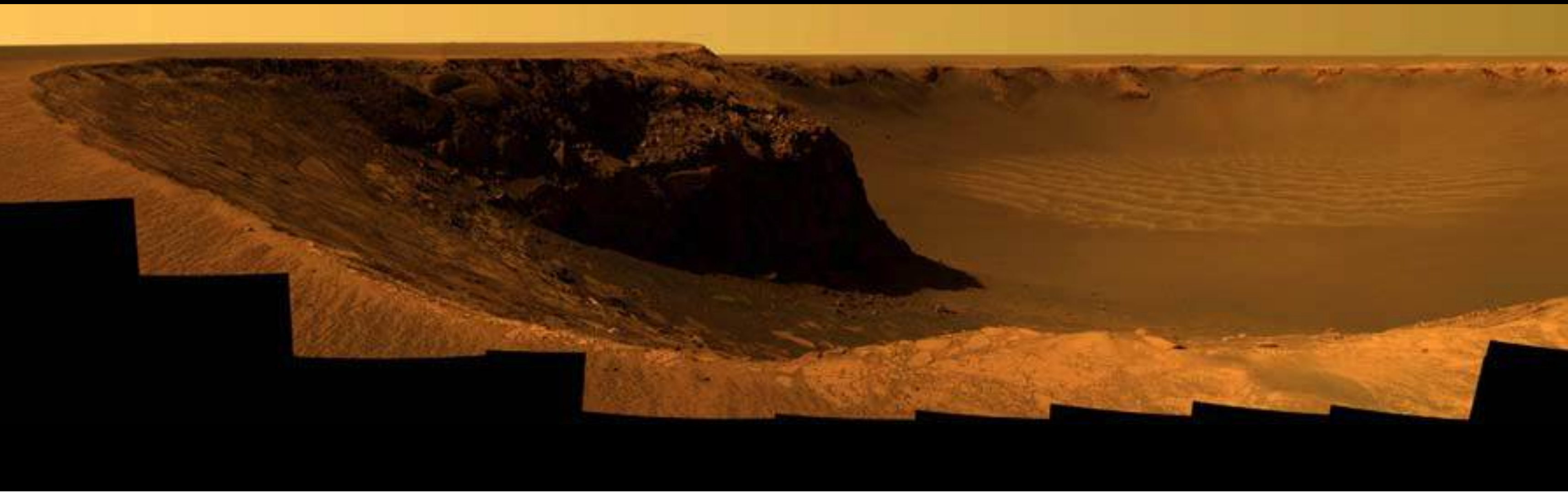
The first three successful landers (Viking 1 and 2 and Pathfinder) landed on lava plains. So did the Spirit rover, but it was able to drive to the Columbia Hills to study different rocks.

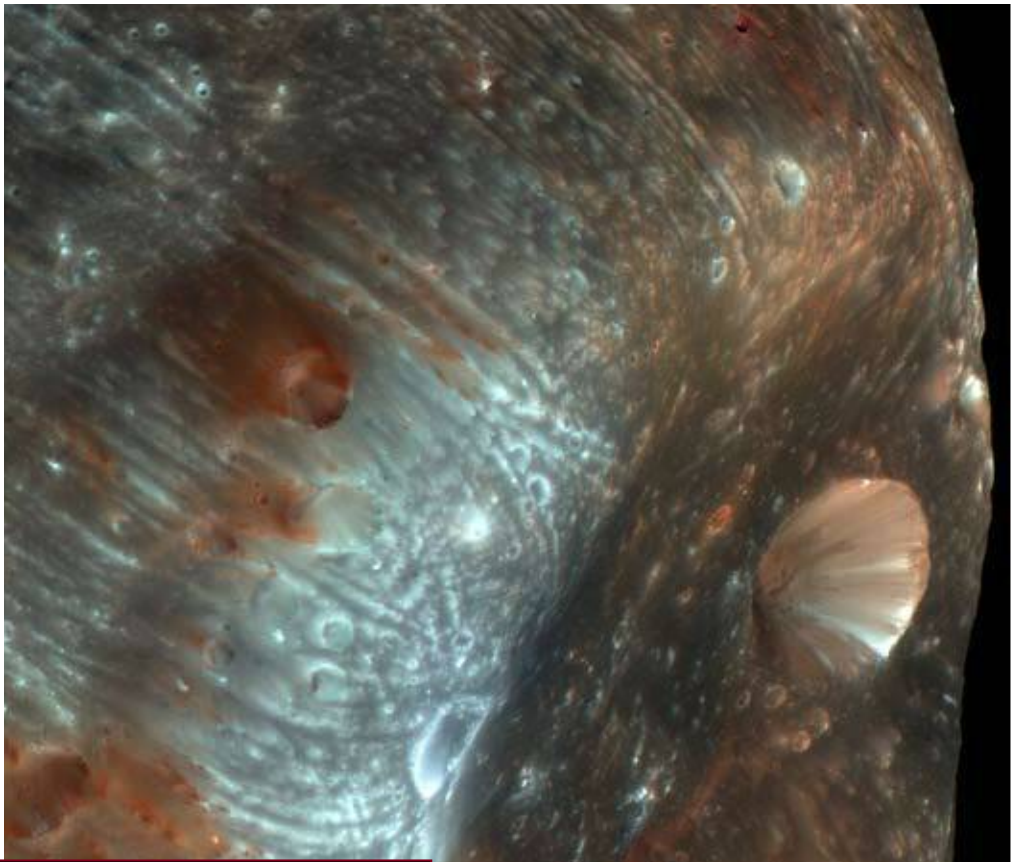
Landing is easiest at lower elevations, because atmospheric pressure is higher there. Because lava has flooded the lowlands, both the mechanics of ejecting rocks from Mars and the landing parameters have combined to present us lava to study up close.

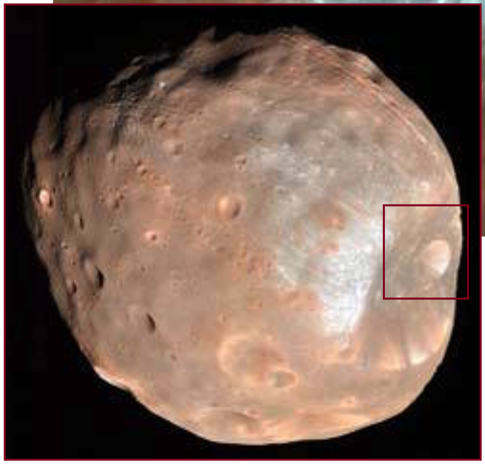
While some researchers like studying lava, it is largely unaltered near the surface and tells us little about the wetter Noachian history of Mars. Noachian is the name of the earliest geologic period, more than 3.8 billion years ago, when heavy bombardment occurred along with widespread river-flow landscape modification. It is named after Mars' Noachis Terra, not the biblical Noah. Still, the connection to water makes this a good mnemonic.

The Spirit and Opportunity rovers have studied some widely divergent rocks. Opportunity landed in Meridiani Planum, a huge region of layered sedimentary deposits. The origin of this layered material remains debatable, but candidates include wind-blown materials, volcanic pyroclastics, sediments deposited by streams or lakes, impact surge deposits, or all of the above. Opportunity has shown that highly acidic water altered these rocks, resulting in sulfur-rich deposits called sulfates.

The imaging spectrometer on the European Mars Express spacecraft has found sulfates in a large region surrounding the volcanic Tharsis area. This makes sense because volcanos spew underground sulfur across the surface. But the spectrometer team found something more interesting at other locations: clay minerals.







◄ **PHOBOS is Mars' largest moon — only 13.6 miles (22.2 km) across. It shows the same cratering as the Red Planet. Above: Astronomers named Stickney Crater, Phobos' largest, for Chloe Angeline Stickney Hall, wife of astronomer Asaph Hall. Asaph Hall discovered Phobos and Mars' other moon, Deimos, in 1877. Stickney Crater spans more than half of Phobos' diameter.** MRO/LPL (UNIV. OF ARIZ.)/NASA

STATISTICS: Mars vs. Earth

	Mars	Earth comparison
Mass	1.415 trillion trillion pounds	10.7% of Earth's
Diameter	4,221 miles	53.2%
Density	3.93 grams/cc	71.3%
Weight of 150-lb person	57 pounds	37.9%
Distance from Sun	141.6 million miles	152.4%
Orbital period	686.98 days	188.1%
Length of day	24.66 hours	102.7%

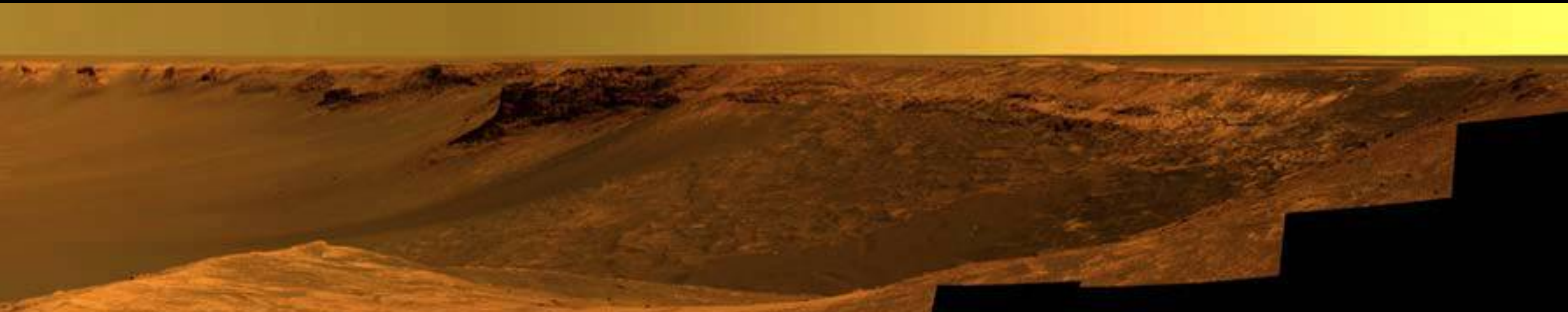
Mass: Total mass (1 trillion = 10^{12}); **Diameter:** Equatorial diameter; **Density:** Average density in grams per cubic centimeter (water = 1); **Distance from Sun:** Average distance; **Orbital period:** Sidereal period; **Length of day:** Average time between successive noons; **Earth comparison:** Ratio of Mars' to Earth's value.

To form, clay minerals require prolonged or intimate exposure to water, so these minerals may point to environments amenable to life. So far, clay minerals have appeared only in ancient Noachian terrains, perhaps because the climate changed. It seems likely that scientists will send a future rover to explore these clay-rich terrains, such as the Nili Fossae region, and perhaps cache samples for eventual return to Earth.

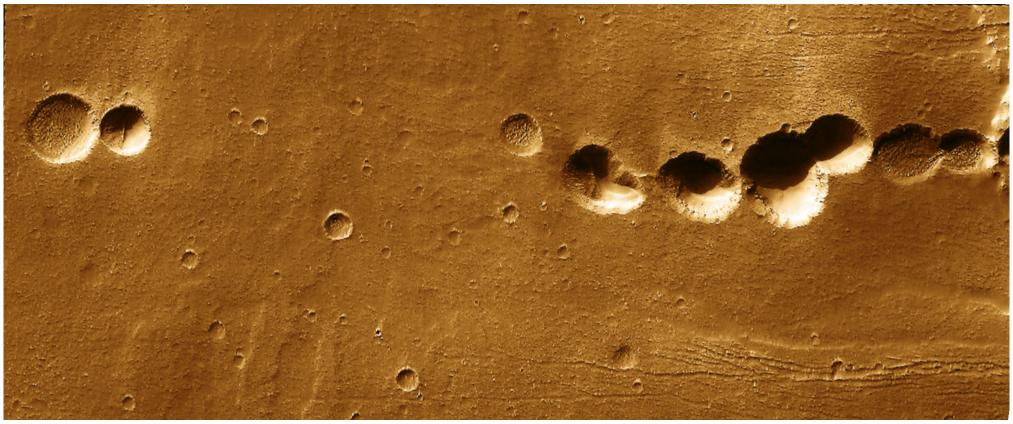
Life on Mars?

Does Mars have life, or did it have life in the past? Some scientists think the development of life on ancient Mars was just as probable as on ancient Earth. The most primitive organisms on the tree of life are thermophiles — organisms that thrive in hot water. Earth experienced the same late heavy bombardment as did the Moon, ending about 3.9 billion years ago. At that time, life probably originated on Earth.

The energy and global effects of the heavy bombardment were extreme, covering the



THE ROVER OPPORTUNITY captured this vista of Victoria Crater from the viewpoint of Cape Verde, one of the promontories on the crater's scalloped rim. The far side of the crater lies about half a mile (800 meters) away. This approximately true-color view combines images taken through three of the Pancam's filters: near infrared, green, and violet. NASA/JPL-CALTECH/CORNELL



▲ A CRATER CHAIN interrupts old lava flow southwest of Alba Patera. Alba Patera is Mars' largest volcano, measuring roughly 1,000 miles (1,600 km) across. Unlike the giant Tharsis volcanos, Alba Patera's lava flows are widespread and its slopes are shallower. The Mars Reconnaissance Orbiter's HiRISE camera acquired this image May 8, 2007. When HiRISE took this picture, the Sun sat only 18° high in Mars' sky, so the crater-wall shadows are well-defined. NASA/JPL/UNIV. OF ARIZONA

planet's surface with molten rock. The only place where organic life could have survived was underground. Because it was shielded from what was happening above, Mars' underground may have been just as hospitable as Earth's.

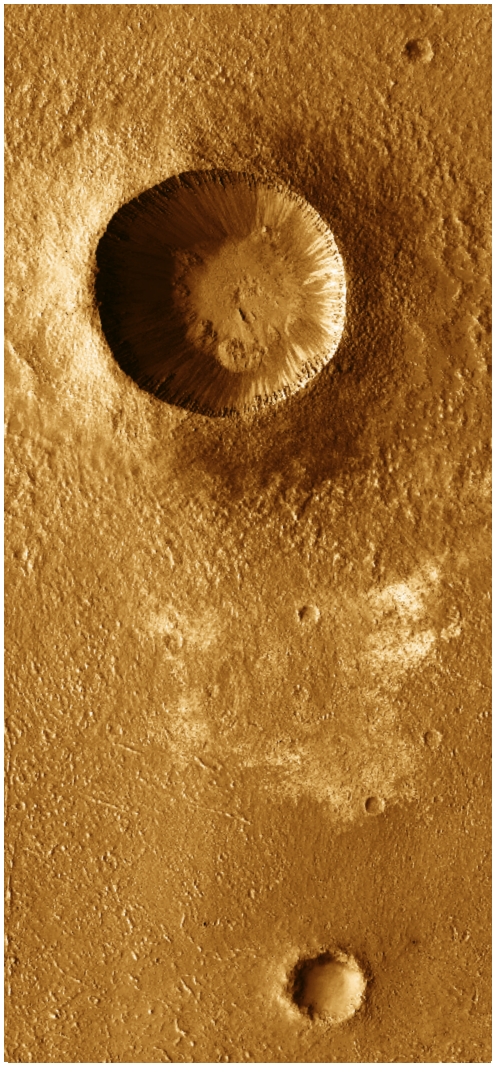
In fact, given the many Mars rocks that must have landed on Earth during the heavy bombardment, some astronomers think life on Earth could have originated on Mars. Some Earth rocks probably landed on Mars as well, but the mechanics are more difficult. In any event, life could have originated on Mars and been transported to Earth, or vice versa.

The big-picture view of Mars' geologic history favored by many scientists has an active Noachian era followed by billions of years of relative quiescence. This view may be oversimplified, but what if it's correct? That would make Mars the ideal planet to study the environments that existed during the period of heavy bombardment, which is when life originated on Earth, Mars, or both planets.

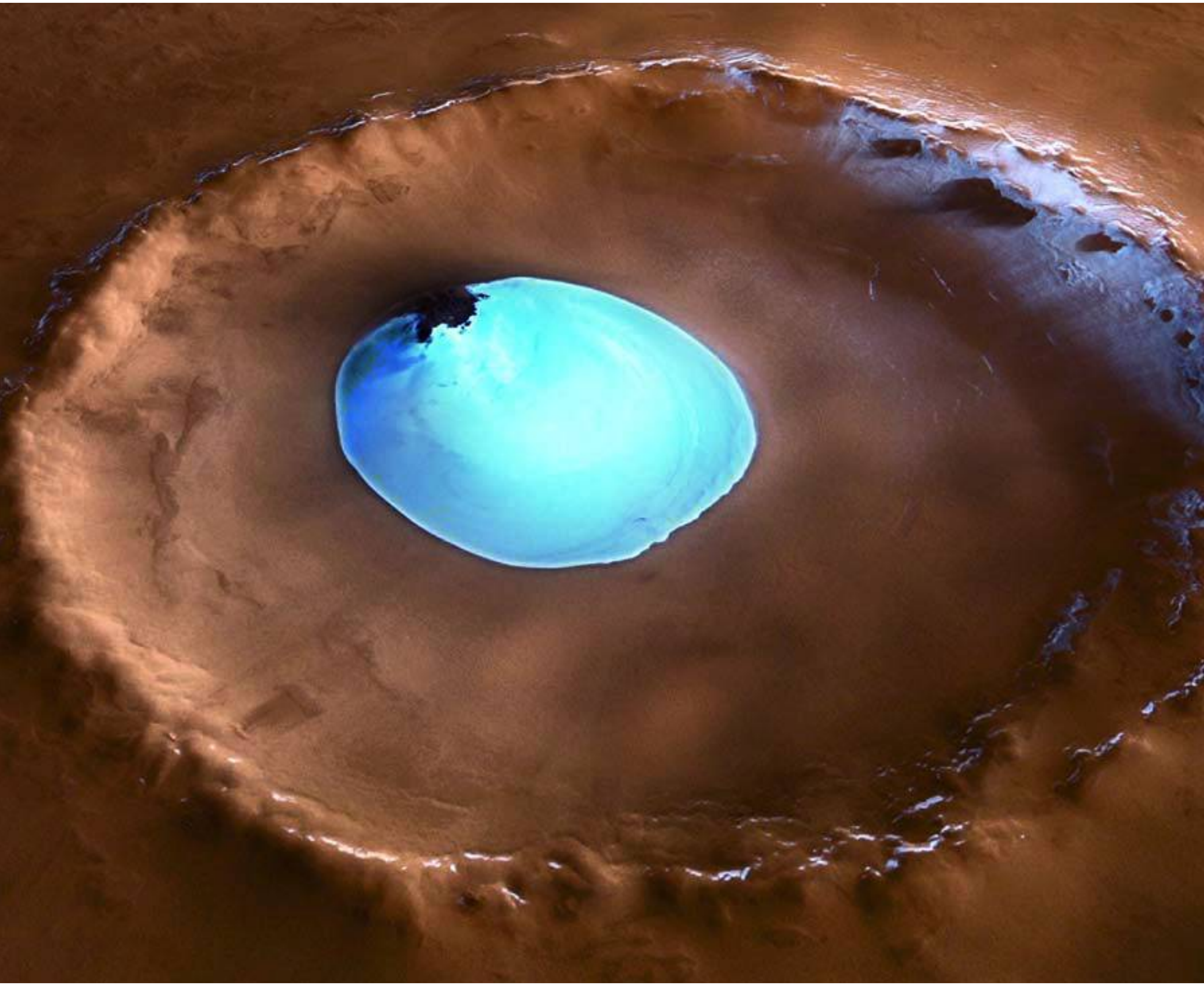
Martian meteorite ALH84001 — discovered at Allan Hills, Antarctica, in December 1984 — is, so far, our only direct sample from that time period. Although NASA scientist David McKay and other astronomers claimed, in 1996, that ALH84001 contains evidence for life, few scientists support that view today. The same scientists, however, continue to argue that Mars may be key to understanding our origin.

Could life exist on Mars today? Life on Earth has persisted in the face of great extremes. If life originated on the Red Planet in the Noachian period, perhaps it is still there. If so, we'll probably find it underground.

An important question is whether or not pockets of shallow groundwater exist. These would breach the surface occasionally to form recent gullies. Most of these gullies are large features, more than tens of meters wide, which would be ravines on Earth. Scientists believe at least some of the gullies required liquid water to form. But where did the water come from?



▲ AT 2 MILES WIDE (3.2 km), Zumba Crater is not Mars' largest impact site. It does boast an impressive ejecta blanket and ray pattern. The crater has streamlined outer structures that resemble fan-shaped deposits in Earth's Mojave Desert where streams exit canyons. The martian structures, however, are smaller and concentrate within the crater's ejecta blanket. NASA/JPL/UNIV. OF ARIZONA



▲ **RESIDUAL WATER ICE SITS ON THE FLOOR of an unnamed impact crater on Vastitas Borealis, a broad plain that covers much of Mars' northern region. Vastitas Borealis sits, on average, 3 to 4 miles (5 to 6 km) below the average radius of Mars. This 22-mile-wide (35 km) crater stands at 70° north latitude. Mars Express' High-Resolution Stereo Camera (HRSC) took this perspective, near-real color view. The vertical relief is 3 times normal.** ESA/DLR/FU BERLIN (G. NEUKUM)

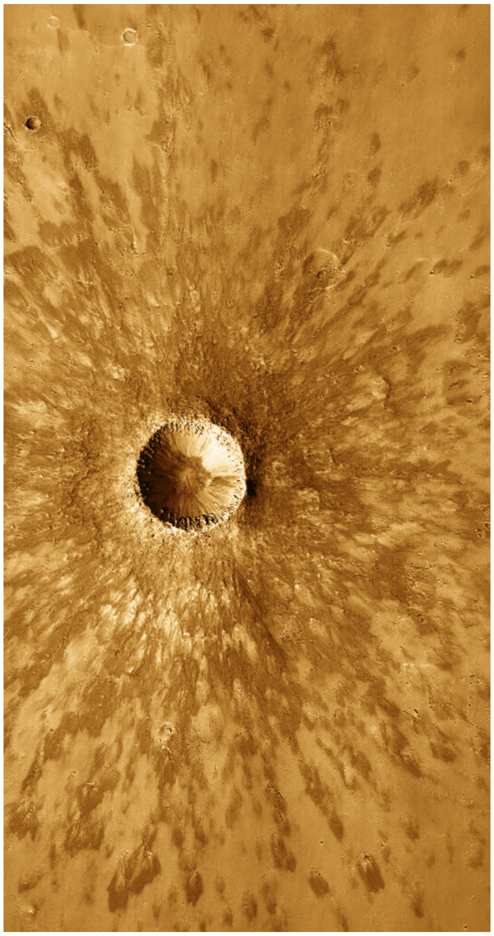
One idea is that conditions allow pockets of groundwater within a few hundred meters of the surface in middle latitudes. Another concept is that, at times of higher orbital obliquity (the tilt of Mars' axis), shallow ice melts.

Both ideas face difficulties with the physics because water is unstable when in contact with the thin martian atmosphere, even beneath hundreds of meters of ground. If the shallow groundwater theory proves correct, perhaps pockets of life exist. Or, maybe martian life can remain dormant for millions of years until the next surface-melting event.

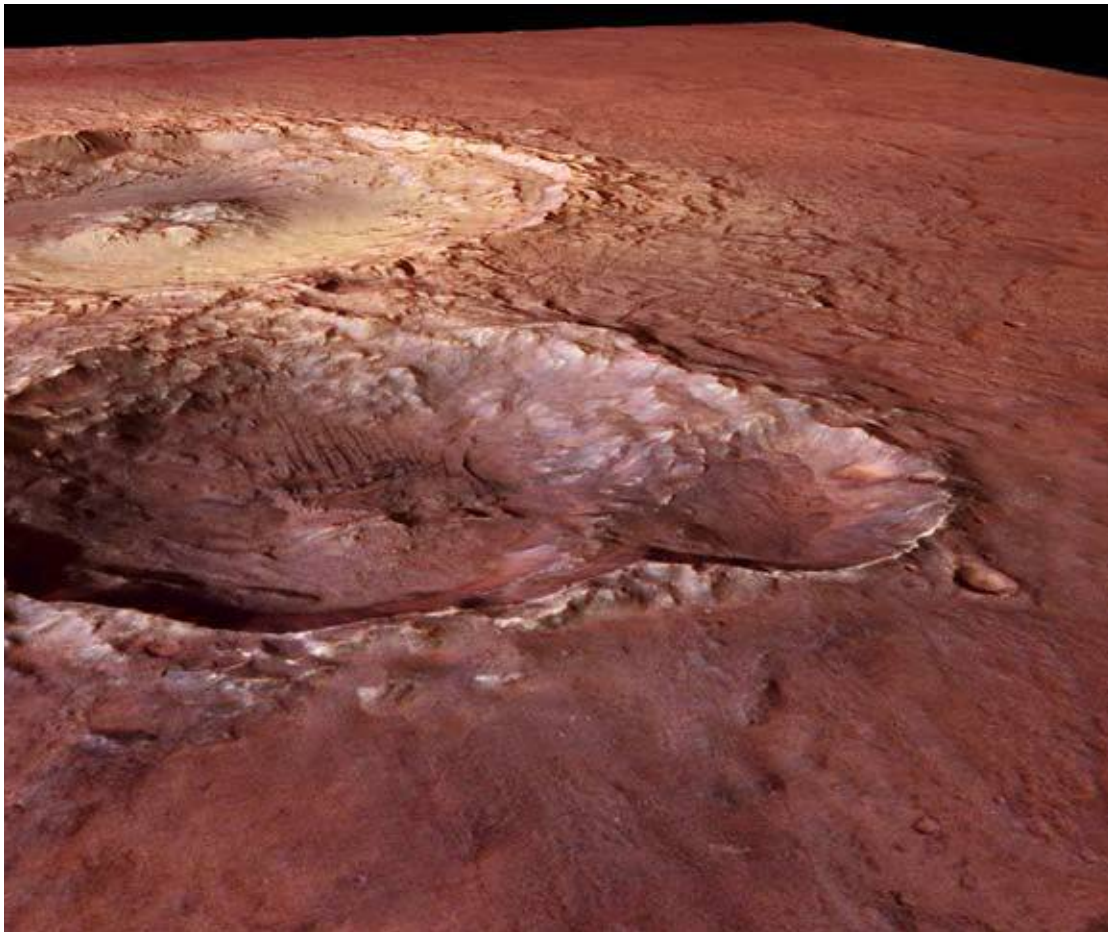
More evidence for martian life seems to exist. The 2004 discovery of trace amounts of methane in the atmosphere by the Gemini South Observatory in Chile created some excitement, but that now seems unconvincing. Independent observers don't regard the methane detections as definitive, and there are nonbiogenic ways to create traces of methane, such as decomposition of certain minerals.

The long road ahead

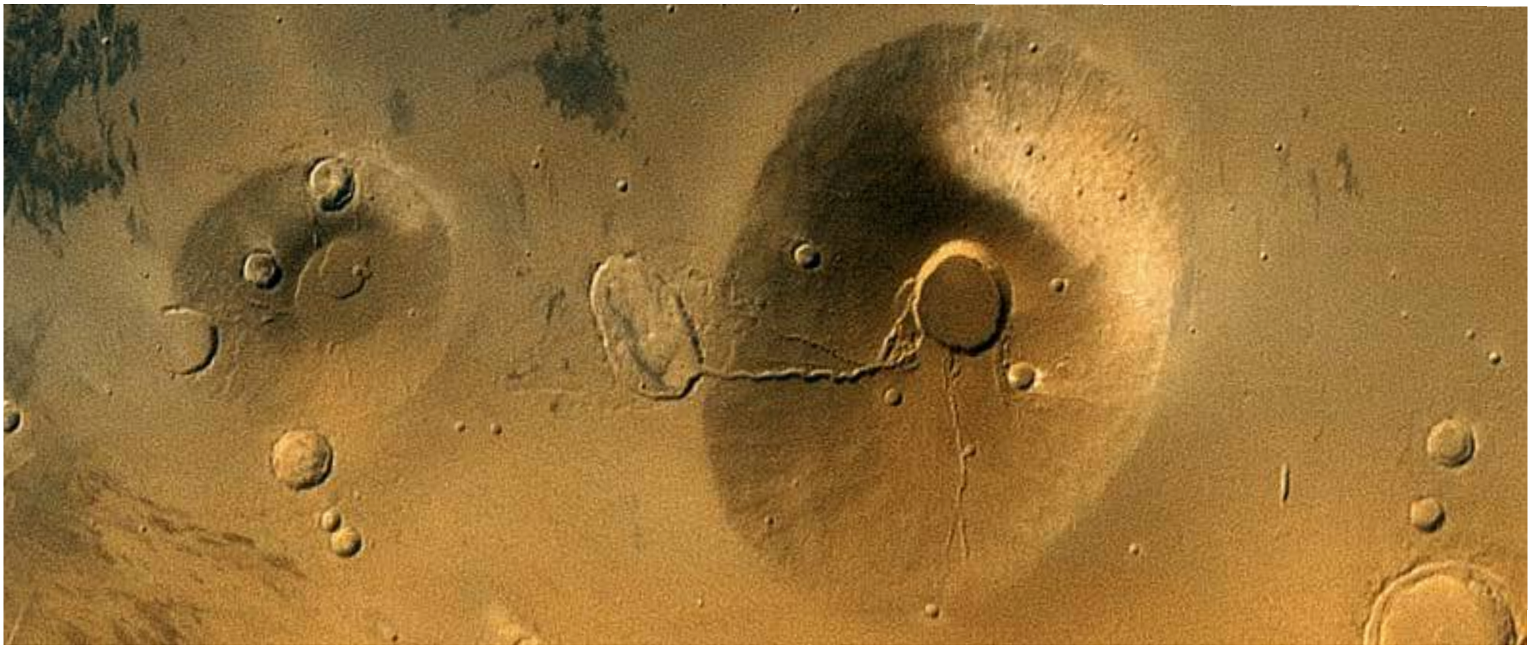
In spite of recent advances, we have a long way to go before we fully understand Mars. Prospects are bright given the interest in continued exploration. Some scientists think returning carefully selected samples from Mars is necessary for major breakthroughs. The returned rocks and soil may raise more questions than they answer, however, which is good. One thing's certain: Mars scientists won't run out of interesting work anytime soon. ◘



▲ **WINSLOW CRATER,** which lies off Syrtis Major, is an example of a recent impact — only about 50,000 years ago. This crater is only slightly larger than Arizona's Meteor Crater and was named for the small town near Meteor Crater. NASA/JPL/UNIV. OF ARIZONA



▲ **TYRRHENA TERRA** is part of the ancient, heavily cratered southern martian highlands. It sits south of Mars' equator, just north of Hellas Planitia, Mars' largest impact basin. A 22-mile-wide (35 km), 4,000-foot-deep (1,000m) impact crater with an extremely steep rim dominates the scene. Multiple layers of material ejected during the impact surround the crater to a distance of 30 miles (50 km). Their round appearance hints at possible ice- and water-rich subsurface material. ESA/DLR/FU BERLIN (G. NEUKUM)



▲ **TWO MARTIAN VOLCANOS,** Uranius Tholus (left) and Ceraunius Tholus (right) dominate this image. The presence of impact craters on these volcanos, particularly on Uranius Tholus, indicates both volcanos are ancient and inactive. The light-toned area on the southeastern face (upper right) of Ceraunius Tholus is a remnant of a once more-extensive deposit of dust from the 2001 martian global dust storm. North is to the left in this image. NASA/JPL/MALIN SPACE SCIENCE SYSTEMS

Secrets of a giant planet

From planet-like moons to storms that last centuries, Jupiter offers scientists a wealth of puzzles. **by John Spencer**

It's been said that the planetary system consists of Jupiter, plus debris. The giant planet, the largest of the Sun's family, is 11 times Earth's diameter and 318 times its mass. Tally up the masses of the other planets and add in those of all the moons, asteroids, and comets, and you'll have less than one-third of the planetary system's total mass. Jupiter alone makes up the rest.

This giant world's gravitational influence not only controls its 63 known moons, but it's also responsible for much of the solar system's architecture. For instance, the asteroid belt between Jupiter and Mars owes its existence to the giant planet's gravity. It stirred up the orbits of rocky debris in the early solar system and prevented it from assembling into a planet. Jupiter also manages a large retinue of so-called Trojan asteroids, which share the planet's orbit around the Sun, and controls the orbits of many known comets.

What's more, the craters on our own Moon and the far-flung orbits of Uranus and Neptune may have been the result of a chaotic period about 4 billion years ago when Jupiter's slowly changing orbital period reached a value exactly half that of Saturn's. This would have caused the two giant planets to deviate wildly from their previous orbits. Their gravitational influence would have scattered a rain of debris into the inner solar system and sent Uranus and Neptune careening to their present locations.

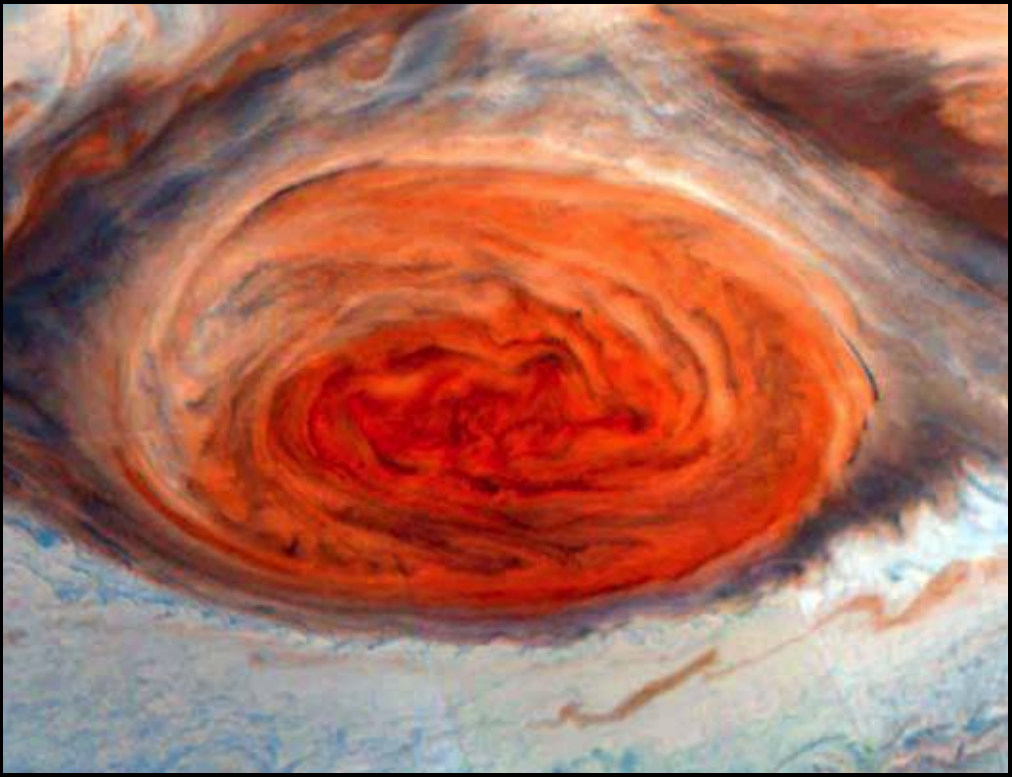
Origin of a giant

Jupiter formed with the rest of the solar system 4.5 billion years ago. It arose from the solar nebula, the swirling cloud of gas and dust that surrounded the young Sun. Near the Sun, where

► **JUPITER IS THE solar system's biggest and most massive planet. Its 10-hour rotation powers oval-shaped storms and whips cloud bands into latitudinal belts.**

NASA/JPL/SSI

John Spencer *is a planetary scientist at the Southwest Research Institute in Boulder, Colorado.*



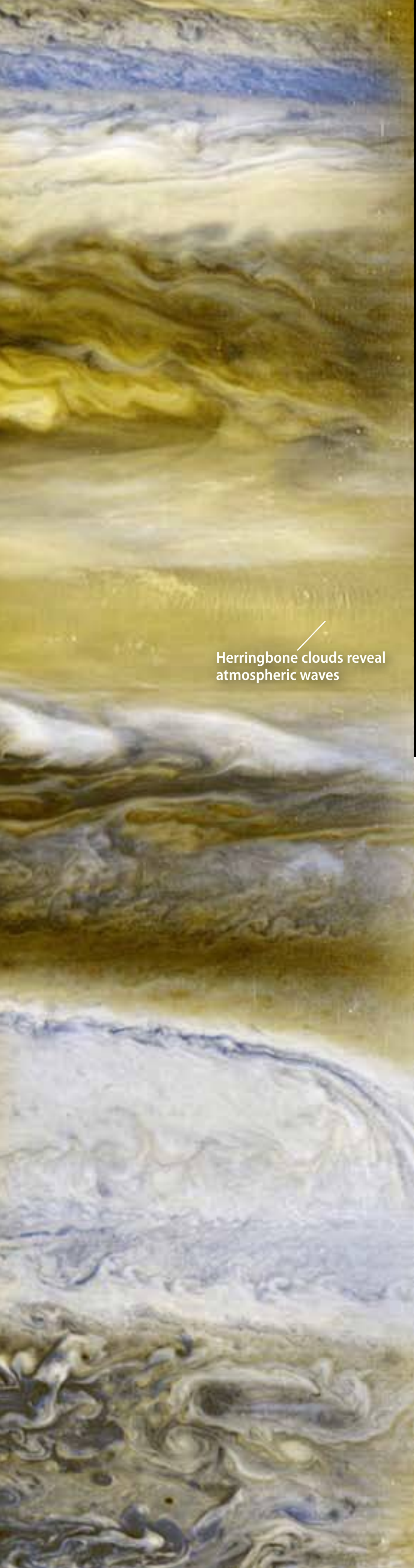
▲ THE GREAT RED SPOT is a persistent high-pressure weather system more than twice Earth's size. Astronomers have observed the feature for at least 180 years. Two smaller red spots have formed in recent years. NASA/JPL

we are, temperatures were hot enough that only rock could condense from the nebula. But at Jupiter's distance, the environment was cold enough that ice could condense as well. So as planets began to form by solid-particle collisions, they grew larger out near Jupiter thanks to the extra material available.

Eventually, one of these protoplanets became large enough that its gravity began to pull in the nebula's gas. It rapidly acquired a huge envelope of mostly hydrogen and helium, the nebula's dominant gases.

So Jupiter, like the Sun but unlike Earth, has a composition similar to the nebula that birthed it. The original solid core that triggered Jupiter's runaway growth probably lies buried at its center, but now it makes up only a small part of the planet's enormous bulk.

The most common element, hydrogen, is so highly compressed deep inside Jupiter that it acts like a metal. Huge electrical currents flow within and generate the planet's powerful magnetic field. Higher up, the pressure relents enough for hydrogen to behave as a more conventional liquid, which grades gradually upward into a gaseous atmosphere. There's nothing we could call a surface.



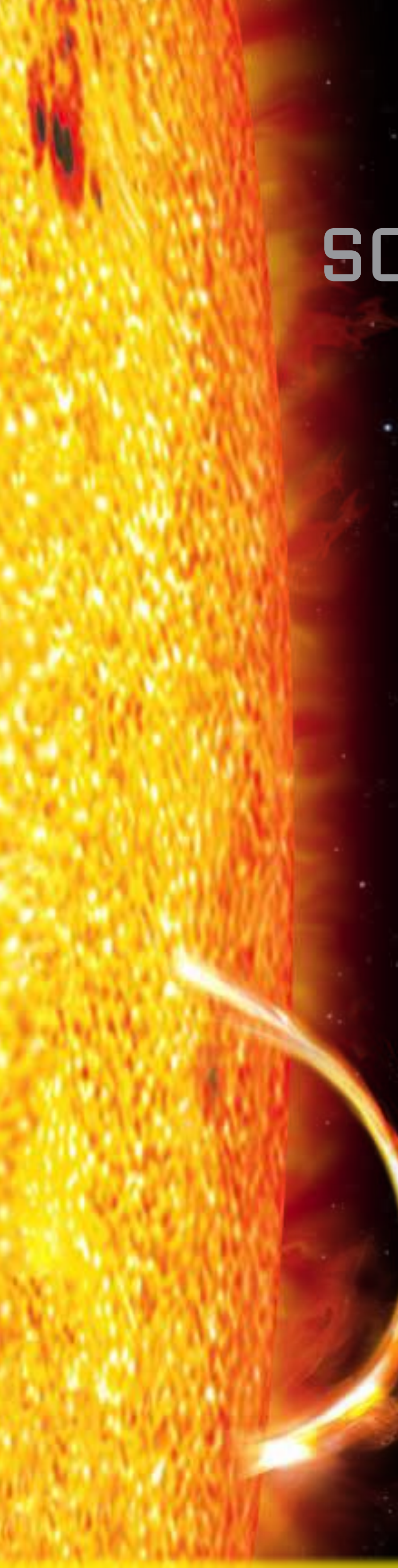
◄ AS NIGHT FELL on Jupiter's stormy skies, the New Horizons spacecraft captured this image of the planet's southern clouds in February 2007. At the equator, a herringbone pattern reveals atmospheric waves from deep in Jupiter's atmosphere. Equatorial cloud features appear more elongated east and west. Small-scale, turbulent, whirlpool-like structures swirl in the south (bottom). NASA/JHUAPL/SWRI

Lots of atmosphere

What we see of Jupiter are its cloud tops. They're sheared into parallel light and dark ribbons by intense alternating east and west winds, which blow up to 330 mph (530 km/h). High-altitude clouds, predominantly made of ammonia at the highest levels, cover the dark bands, which scientists call belts. The bright bands (zones) are relatively cloud-free. This allows researchers to see lower cloud layers, which probably include large fractions of water.

Oval anticyclonic (high pressure) storms break up the belts and zones. For some reason, they're much more common in the southern hemisphere than in the northern. The most famous of these is, of course, the Great Red Spot, which is at least 180 years old — astonishingly long-lived by the standards of terrestrial meteorology.

Between 1998 and 2000, three small storms coalesced into a single white oval. Then, in 2005,



Atlas of the solar system: Planets

From big and gaseous to small and rocky, the solar system's eight planets offer scientists a dazzling variety.

by Richard Talcott

Few astronomical discoveries are lost in the mists of prehistory. The bright planets rank at the top of this short list. Most ancient civilizations recognized five objects that behaved differently from the stars: Mercury, Venus, Mars, Jupiter, and Saturn. The word *planet* hints why. It comes from a Greek word meaning "wanderer" — the planets move relative to the background stars.

The solar system contained six planets (add Earth to the mix) until the 18th century. On March 13, 1781, amateur astronomer William Herschel spied an object through his telescope that appeared as a small disk instead of a stellar point. He tracked its motion for a few weeks, and calculations soon showed it orbits the Sun on a nearly circular path well beyond Saturn. Uranus, as it came to be known, was lucky planet seven.

Number eight seemed to arrive 2 decades later. On January 1, 1801, Italian Giuseppe Piazzi found an object in the large gap separating Mars and Jupiter. It seemed to be the long-sought "missing planet." In the years that followed, however, several more objects turned up in the so-called gap, and Ceres and the others were demoted to "minor planets," or asteroids.

The number rebounded to eight with the September 1846 discovery of Neptune. Two mathematicians, John Adams from England and Urbain Leverrier from France, who calculated its orbit, share credit for the discovery with Heinrich d'Arrest from Germany, who spotted it through his telescope.

Astronomers added number nine in February 1930, when American Clyde Tombaugh discovered Pluto. Unfortunately, Pluto met Ceres' fate. In August 2006, the International Astronomical Union voted on a new definition of a planet, and Pluto was too small. It now qualifies as a "dwarf planet," along with Ceres and Eris, an icy object that orbits the Sun far beyond Pluto. So we stand at eight planets in 2008 — but there's no guarantee where we'll find ourselves in the future. ◻

Mercury

Equatorial diameter: 3,032 miles (0.382 Earth)
Mass: 0.726 trillion trillion pounds (0.055 Earth)
Average density: 5.43 g/cc (0.984 Earth)
Average distance from the Sun: 35.98 million miles (0.387 Earth)
Orbital period: 87.969 days (0.241 Earth)
Orbital eccentricity: 0.206
Orbital inclination: 7°
Length of day: 4,222.6 hours (175.94 Earths)
Number of moons: 0

NASA/JHUAPL/CIW

Venus

Equatorial diameter: 7,521 miles (0.949 Earth)
Mass: 10.71 trillion trillion pounds (0.815 Earth)
Average density: 5.24 g/cc (0.951 Earth)
Average distance from the Sun: 67.24 million miles (0.723 Earth)
Orbital period: 224.701 days (0.615 Earth)
Orbital eccentricity: 0.007
Orbital inclination: 3.39°
Length of day: 2,802.0 hours (116.75 Earths)
Number of moons: 0

NASA/JPL

Earth

Equatorial diameter: 7,926 miles
Mass: 13.14 trillion trillion pounds
Average density: 5.52 g/cc
Average distance from the Sun: 92.96 million miles
Orbital period: 365.256 days
Orbital eccentricity: 0.017
Orbital inclination: 0.00°
Length of day: 24 hours
Number of moons: 1

NASA

Mars

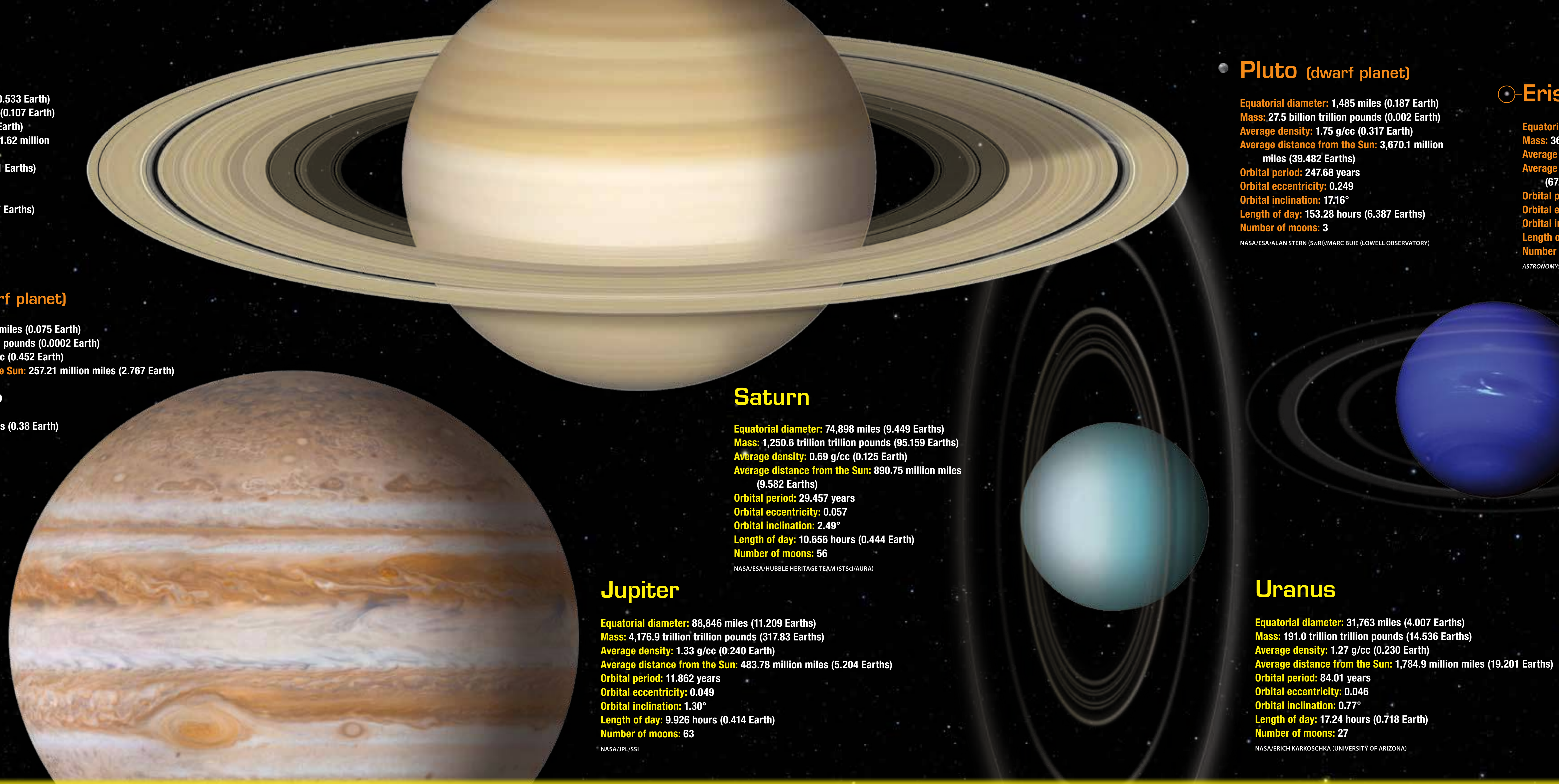
Equatorial diameter: 4,222 miles (0.533 Earth)
Mass: 1.412 trillion trillion pounds (0.107 Earth)
Average density: 3.93 g/cc (0.713 Earth)
Average distance from the Sun: 141.62 million miles (1.512 Earths)
Orbital period: 686.980 days (1.881 Earths)
Orbital eccentricity: 0.094
Orbital inclination: 1.85°
Length of day: 24.660 hours (1.027 Earths)
Number of moons: 2

ESA/ROSETTA

Ceres (dwarf planet)

Equatorial diameter: 597 miles (0.075 Earth)
Mass: 1.914 billion trillion pounds (0.0002 Earth)
Average density: 2.49 g/cc (0.452 Earth)
Average distance from the Sun: 257.21 million miles (2.767 Earth)
Orbital period: 4.6 years
Orbital eccentricity: 0.079
Orbital inclination: 10.58°
Length of day: 9.075 hours (0.38 Earth)
Number of moons: 0

NASA/ESA



Saturn

Equatorial diameter: 74,898 miles (9.449 Earths)
Mass: 1,250.6 trillion trillion pounds (95.159 Earths)
Average density: 0.69 g/cc (0.125 Earth)
Average distance from the Sun: 890.75 million miles (9.582 Earths)
Orbital period: 29.457 years
Orbital eccentricity: 0.057
Orbital inclination: 2.49°
Length of day: 10.656 hours (0.444 Earth)
Number of moons: 56

NASA/ESA/HUBBLE HERITAGE TEAM (STScI/AURA)

Jupiter

Equatorial diameter: 88,846 miles (11.209 Earths)
Mass: 4,176.9 trillion trillion pounds (317.83 Earths)
Average density: 1.33 g/cc (0.240 Earth)
Average distance from the Sun: 483.78 million miles (5.204 Earths)
Orbital period: 11.862 years
Orbital eccentricity: 0.049
Orbital inclination: 1.30°
Length of day: 9.926 hours (0.414 Earth)
Number of moons: 63

NASA/JPL/SSI

Pluto (dwarf planet)

Equatorial diameter: 1,485 miles (0.187 Earth)
Mass: 27.5 billion trillion pounds (0.002 Earth)
Average density: 1.75 g/cc (0.317 Earth)
Average distance from the Sun: 3,670.1 million miles (39.482 Earths)
Orbital period: 247.68 years
Orbital eccentricity: 0.249
Orbital inclination: 17.16°
Length of day: 153.28 hours (6.387 Earths)
Number of moons: 3

NASA/ESA/ALAN STERN (SwRI)/MARC BUIE (LOWELL OBSERVATORY)

Uranus

Equatorial diameter: 31,763 miles (4.007 Earths)
Mass: 191.0 trillion trillion pounds (14.536 Earths)
Average density: 1.27 g/cc (0.230 Earth)
Average distance from the Sun: 1,784.9 million miles (19.201 Earths)
Orbital period: 84.01 years
Orbital eccentricity: 0.046
Orbital inclination: 0.77°
Length of day: 17.24 hours (0.718 Earth)
Number of moons: 27

NASA/ERICH KARKOSCHKA (UNIVERSITY OF ARIZONA)

Astronomy magazine

Eris (dwarf planet)

Equatorial diameter: 1,616 miles (0.20 Earth)
Mass: 36.7 billion trillion pounds (0.003 Earth)
Average density: 2.3 g/cc (0.42 Earth)
Average distance from the Sun: 6,301 million miles (67.784 Earths)
Orbital period: 558 years
Orbital eccentricity: 0.439
Orbital inclination: 44.12°
Length of day: unknown
Number of moons: 1

ASTRONOMY: ROEN KELLY

Neptune

Equatorial diameter: 30,775 miles (3.883 Earths)
Mass: 225.3 trillion trillion pounds (17.147 Earths)
Average density: 1.64 g/cc (0.297 Earth)
Average distance from the Sun: 2,793.1 million miles (30.047 Earths)
Orbital period: 164.79 years
Orbital eccentricity: 0.011
Orbital inclination: 1.77°
Length of day: 16.11 hours (0.671 Earth)
Number of moons: 13

NASA/JPL

Orbits of the planets

ILLUSTRATION: *ASTRONOMY*: ROEN KELLY

Mercury
Venus
Earth
Sun
Mars
Ceres
Jupiter
Saturn
Uranus
Neptune
Pluto
Eris
Miles
500 million
1 billion
1.5 billion
2 billion
2.5 billion
3 billion
3.5 billion
4 billion
4.5 billion
5 billion
5.5 billion
6 billion

Atlas of the solar system: Small bodies

Here's everything you need to know about the solar system's many moons, asteroids, and comets.

by Richard Talcott

When it comes to the solar system, you have the Sun and then everything else. And not much of the latter: The Sun contributes 99.8 percent of the solar system's mass. Jupiter pulls much the same trick among the planets, holding more than twice as much material as all the others combined.

That doesn't leave much for the rest of our system: moons, asteroids, comets, and assorted smaller debris. Yet many of these objects climb to the top of any list of the solar system's most intriguing objects. Earth's Moon, for example, shines brighter than any other object in the night sky. Its battered face tells a story of repeated and powerful impacts. This was scientists' first clue that our neighborhood isn't as benign as it might appear.

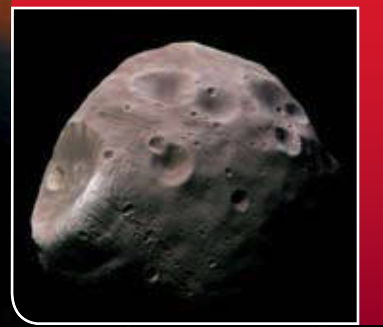
Astronomers discovered other moons as soon as they first pointed their telescopes to the heavens. In 1610, Galileo discovered four moons circling Jupiter — the first proof that Earth was not the center of all motion in the universe.

More moons soon followed, as astronomers trained ever-larger telescopes on the planets. With the exceptions of Mercury and Venus, every planet has at least one moon, and half have more than a dozen.

Within the past few decades, spacecraft revealed many of these moons as worlds themselves. Erupting volcanos, bizarre landforms, underground oceans of water, and surface lakes of liquid methane are just some of the unexpected wonders out there.

Meanwhile, asteroids and comets offer scientists a look back to the solar system's beginnings, some 4.6 billion years ago. And anyone who saw Comet Hale-Bopp in 1997 or Comet C/2006 P1 (McNaught) in 2007 can testify to the thrills these objects generate. In our solar system, sometimes the best things come in small packages. ◘

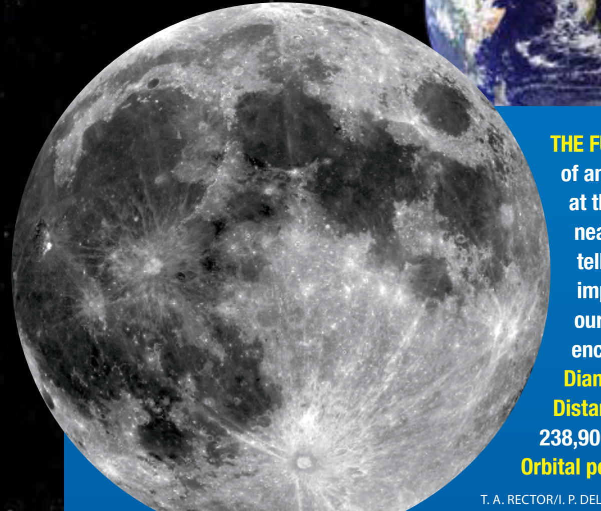
Mars



CRATERED PHOBOS, with its irregular shape and battered surface, resembles most of the small moons in the solar system.
Diameter: 17 miles
Distance from Mars: 5,827 miles
Orbital period: 7.65 hours

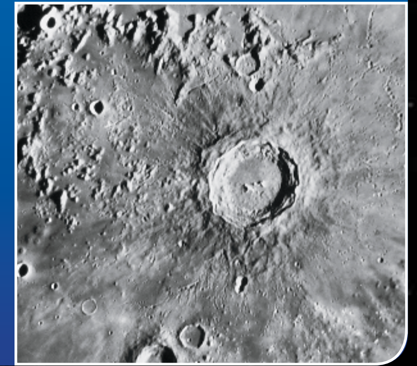
ESA/DLR/FU BERLIN (G. NEUKUM)

Earth



THE FULL MOON dazzles the eyes of anyone who looks skyward at the right time of month. The nearest celestial object to Earth tells a tale of countless impacts — and reveals what our planet must have experienced early in its history.
Diameter: 2,160 miles
Distance from Earth: 238,900 miles
Orbital period: 27.32 days

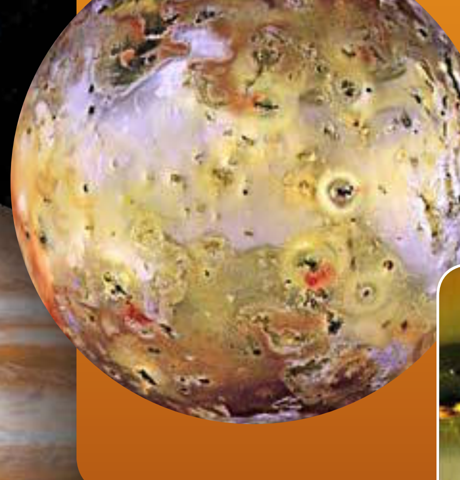
T. A. RECTOR/I. P. DELL'ANTONIO/NOAO/AURA/NSF



COPERNICUS CRATER dates from only a billion years ago, making it one of the Moon's youngest major craters. It measures 58 miles (93 km) across.

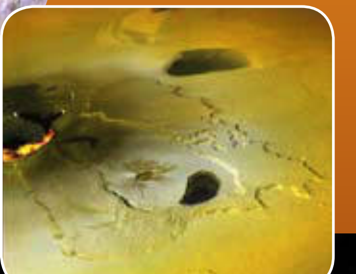
CONSOLIDATED LUNAR ATLAS/LPL/UA

Jupiter

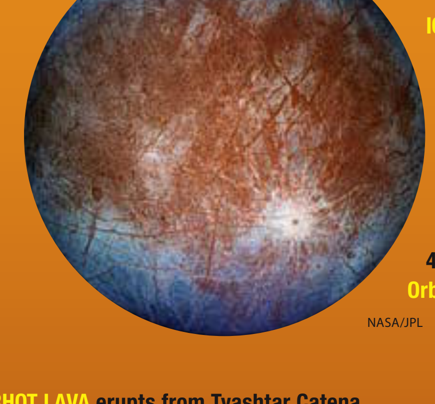


PIZZA-FACED IO is the most volcanically active object in the solar system. Strong tidal forces from Jupiter cause volcanos to spew plumes hundreds of miles into this moon's airless sky.
Diameter: 2,264 miles
Distance from Jupiter: 262,000 miles
Orbital period: 1.77 days

NASA/JPL

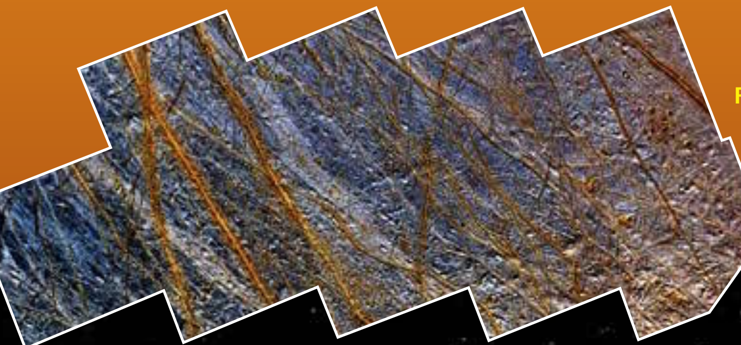


SUPERHOT LAVA erupts from Tvashtar Catena, one of Io's more than 100 active volcanos. The yellow-orange ribbon of lava at left stretches some 37 miles (60 km) long, while older, cooler flows flood the surroundings. NASA/JPL



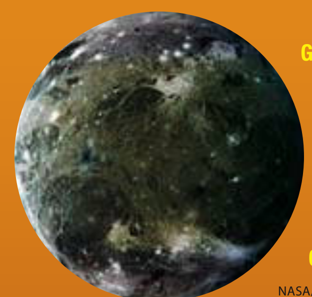
ICY EUROPA has one of the smoothest surfaces in the solar system. Tidal forces from Jupiter melt the ice beneath the frigid surface, creating an ocean that may contain as much liquid water as all of Earth's oceans.
Diameter: 1,940 miles
Distance from Jupiter: 416,900 miles
Orbital period: 3.55 days

NASA/JPL



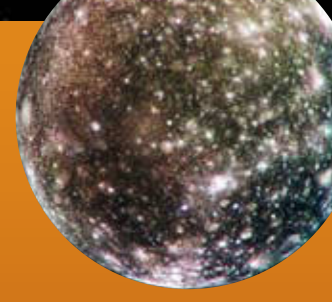
RIDGES SCAR much of Europa's surface. Such ridges could be sites where slushy water erupted through the icy surface and then froze.

NASA/JPL



GANYMEDE'S GROOVED TERRAIN dominates the center of the moon's trailing hemisphere. It appears tan in this enhanced image, while older, furrowed terrain appears dark.
Diameter: 3,270 miles
Distance from Jupiter: 665,100 miles
Orbital period: 7.15 days

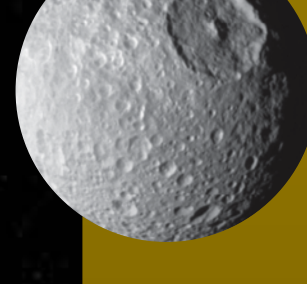
NASA/JPL



BATTERED CALLISTO is the most cratered object known in the solar system. Craters are so densely packed that, whenever an object impacts Callisto, it destroys as many preexisting craters as it creates.
Diameter: 2,995 miles
Distance from Jupiter: 1,169,900 miles
Orbital period: 16.69 days

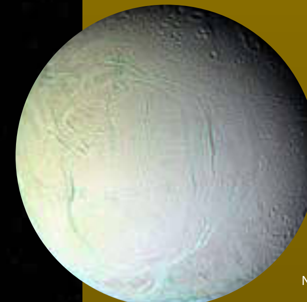
NASA/JPL

Saturn



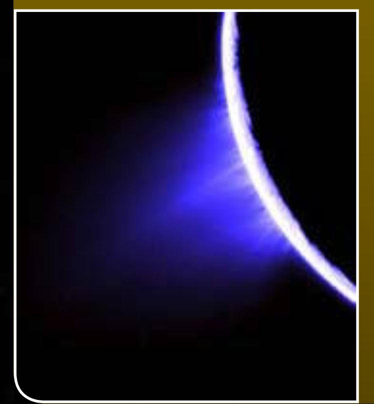
TINY MIMAS — Saturn's innermost major moon — sports a huge impact crater named Herschel. At 88 miles (140 km) across, Herschel spans one-third of Mimas' diameter.
Diameter: 260 miles
Distance from Saturn: 115,300 miles
Orbital period: 22.6 hours

NASA/JPL/SSI



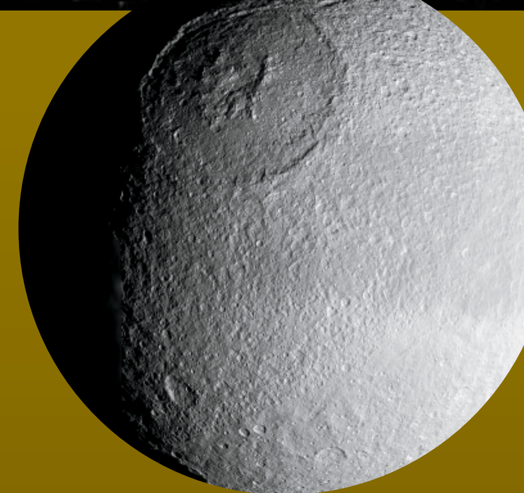
ICE-RICH ENCELADUS harbors liquid water not too far beneath its surface. The bluish "tiger stripes" seen in the uncratered part of the moon's trailing hemisphere run at least 207° F (115° C) warmer than the rest of the moon.
Diameter: 318 miles
Distance from Saturn: 147,900 miles
Orbital period: 1.37 days

NASA/JPL/SSI



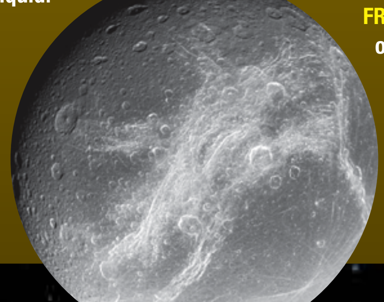
WATER VAPOR, ice particles, and organic molecules spurt from the tiger stripes on Enceladus' surface. These jets reflect a warm interior, where water can exist as a liquid.

NASA/JPL/SSI



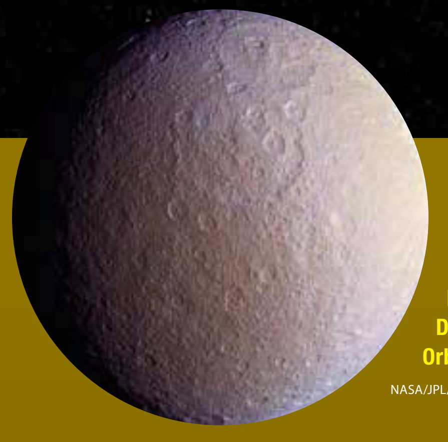
TETHYS' SCARS offer testimony to the battering most solar system moons have experienced. Tethys' largest crater, Odysseus, spans 280 miles (450 km) and features two rings that formed from the impact and its resulting shock waves.
Diameter: 666 miles
Distance from Saturn: 183,100 miles
Orbital period: 1.89 days

NASA/JPL/SSI



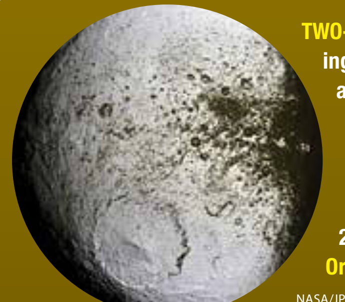
FRACTURED DIONE features a tortured complex of braided canyons with bright walls. This view shows the moon's rugged trailing hemisphere.
Diameter: 696 miles
Distance from Saturn: 234,500 miles
Orbital period: 2.74 days

NASA/JPL/SSI



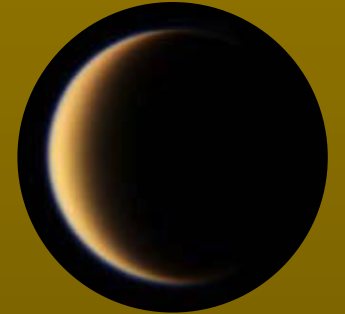
ANCIENT RHEA ranks as Saturn's second-largest moon. The two large impact basins near the top are littered with many smaller craters, evidence of the basins' great age.
Diameter: 950 miles
Distance from Saturn: 327,500 miles
Orbital period: 4.52 days

NASA/JPL/SSI



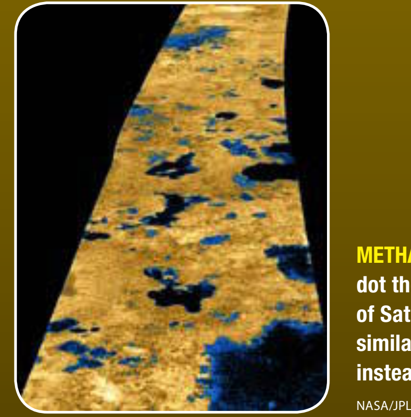
TWO-FACED IAPETUS features a trailing hemisphere of bright white ice and a leading hemisphere (far right) covered with a thin veneer of dark carbon-rich compounds.
Diameter: 892 miles
Distance from Saturn: 2,212,900 miles
Orbital period: 79.33 days

NASA/JPL/SSI



HAZE-SHROUDED TITAN is the only solar system moon with a substantial atmosphere. The nitrogen-rich air has a surface pressure some 50-percent greater than Earth's.
Diameter: 3,200 miles
Distance from Saturn: 759,200 miles
Orbital period: 15.95 days

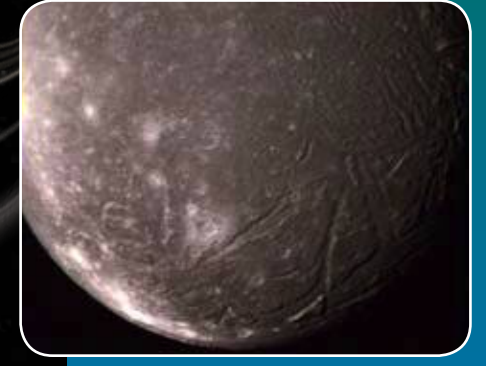
NASA/JPL/SSI



METHANE LAKES (blue in this radar image) dot the polar regions of Titan. The largest of Saturn's moons has a weather cycle similar to Earth, but based on methane instead of water.

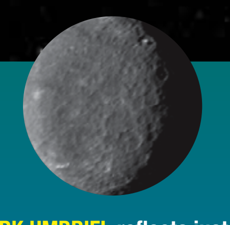
NASA/JPL/USGS

Uranus



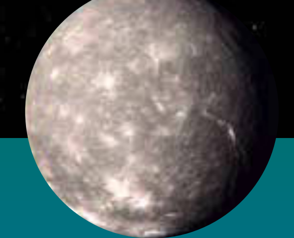
ARIEL'S SOUTHERN HEMISPHERE presents a complex landscape of intensely cratered terrain cut by high cliffs and deep valleys formed through geological faulting.
Diameter: 722 miles
Distance from Uranus: 118,700 miles
Orbital period: 2.52 days

NASA/JPL



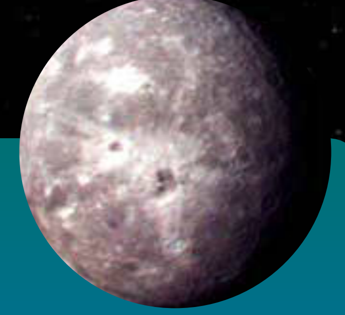
DARK UMBRIEL reflects just 16 percent of the sunlight reaching it. Ubiquitous craters tell scientists that Umbriel has seen less geological activity than any large uranian moon.
Diameter: 727 miles
Distance from Uranus: 165,500 miles
Orbital period: 4.14 days

NASA/JPL



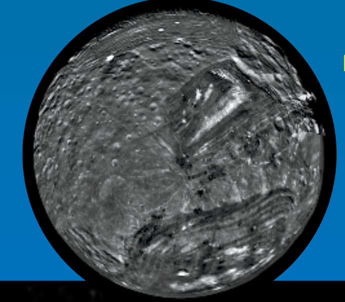
POCKMARKED TITANIA, Uranus' biggest moon, has several craters with bright rays — a sign of their relatively recent origin. The trench at far right hints at some tectonic activity.
Diameter: 980 miles
Distance from Uranus: 270,900 miles
Orbital period: 8.71 days

NASA/JPL



OBERON'S BRIGHT CRATERS testify to this moon's icy surface. The large crater just below center sports a bright central peak and a floor partially covered with dark material.
Diameter: 946 miles
Distance from Uranus: 362,600 miles
Orbital period: 13.46 days

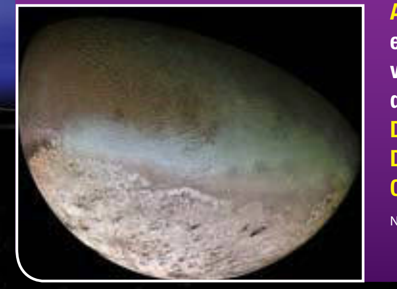
NASA/JPL



DIVERSE MIRANDA breaks into two distinct sections: an old, heavily cratered terrain (left) and a younger, complex terrain of high cliffs and deep canyons.
Diameter: 298 miles
Distance from Uranus: 80,700 miles
Orbital period: 1.41 days

NASA/JPL

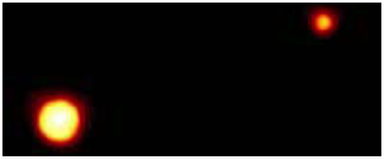
Neptune



ACTIVE TRITON, Neptune's largest moon by far, has erupting geysers (which deposited the dark streaks visible in this image's bottom half) and a surface dominated by nitrogen frost.
Diameter: 1,682 miles
Distance from Neptune: 220,400 miles
Orbital period: 5.88 days

NASA/JPL/USGS

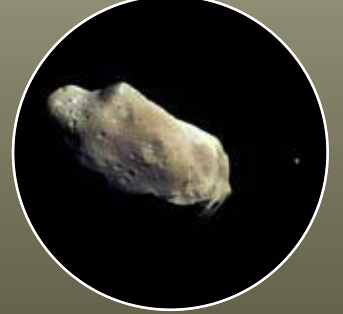
Pluto



FAINT CHARON (upper right) is nearly half the size of the dwarf planet Pluto, making these two the most closely matched pair of major objects in the solar system.
Diameter: 737 miles
Distance from Pluto: 12,200 miles
Orbital period: 6.39 days

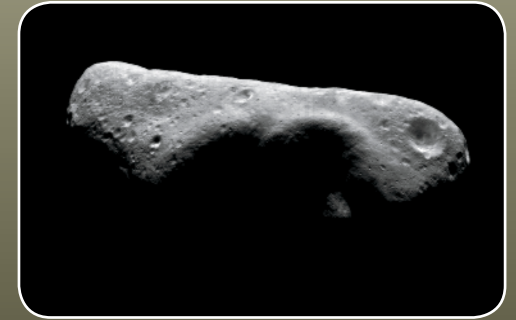
NASA/ESA/R. ALBRECHT

Asteroids and comets



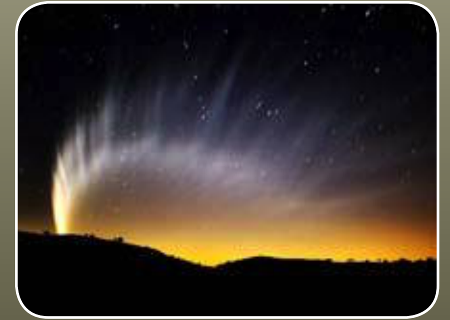
ASTEROID 243 IDA was the first asteroid found to have a moon. Diminutive Dactyl sits to Ida's right in this Galileo image.

NASA/JPL



ASTEROID 433 EROS ranks among the largest of the near-Earth asteroids, and one day in the distant future could strike our planet. The NEAR-Shoemaker spacecraft orbited Eros in 2000 and 2001.

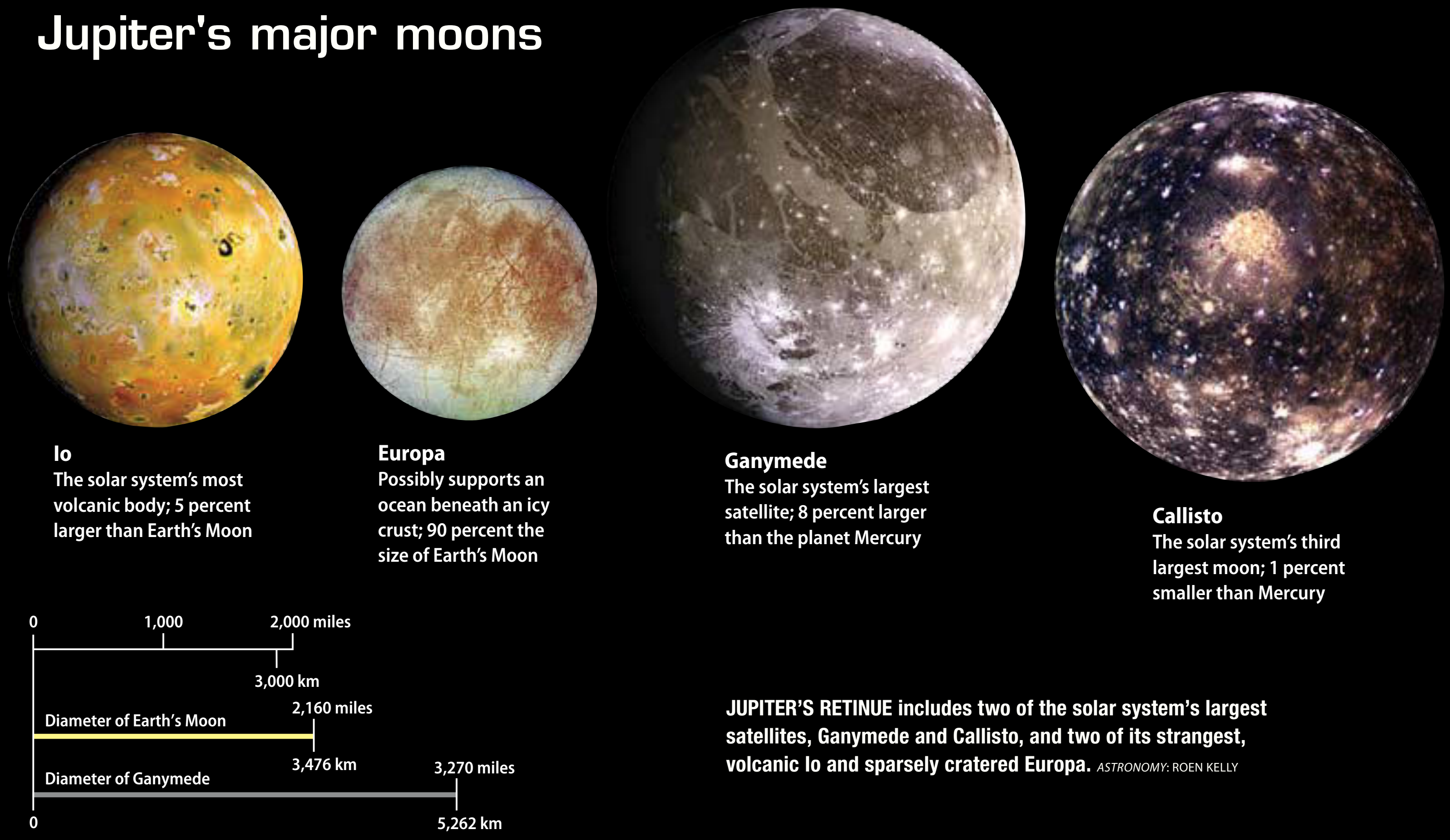
NASA/JPL/JHUAPL



COMET C/2006 P1 (McNAUGHT) wowed Southern Hemisphere observers in January 2007. Its immense dust tail stretched more than 20° high and 30° wide.

MIKE SALWAY

Astronomy magazine


Jupiter's major moons
Io
The solar system's most volcanic body; 5 percent larger than Earth's Moon
Europa
Possibly supports an ocean beneath an icy crust; 90 percent the size of Earth's Moon
Ganymede
The solar system's largest satellite; 8 percent larger than the planet Mercury
Callisto
The solar system's third largest moon; 1 percent smaller than Mercury
0
1,000
2,000 miles
3,000 km
Diameter of Earth's Moon
2,160 miles
3,476 km
Diameter of Ganymede
3,270 miles
0
5,262 km

JUPITER'S RETINUE includes two of the solar system's largest satellites, Ganymede and Callisto, and two of its strangest, volcanic Io and sparsely cratered Europa. *ASTRONOMY*: ROEN KELLY

amateur astronomers noticed the storm was turning red. Now dubbed the "Little Red Spot," it's roughly half the size of its larger cousin.

In 2008, Jupiter acquired yet another new red spot. Scientists don't know why such changes occur, and even the red color of these large storms remains mysterious. The best explanation so far is that sulfur compounds, dredged up from deep below by the storms' intense winds, provide the vivid color.

The moons of Galileo

Of Jupiter's 63 known satellites, four reign supreme — the planet-sized Galilean moons, named collectively for their discoverer, Galileo Galilei (1564–1642). Their individual names, moving outward from Jupiter, are Io, Europa, Ganymede, and Callisto. Each is comparable to or larger than our own Moon.

These satellites appear to have condensed from the nebula surrounding Jupiter when it formed in much the same way the planets formed from the nebula encircling the Sun. The character of the moons changes progressively with distance from Jupiter. This is partly due to varying initial composition: The moons farther from Jupiter's warmth contain more ice.

Jupiter's tides constitute its most profound influence on these worlds. The three inner moons — Io, Europa, and Ganymede — are locked into a simple 4:2:1 mathematical dance by their mutual gravitational pulls. For every orbit Ganymede makes around Jupiter, Europa orbits twice, and Io orbits four times. The moons' rhythmic tugs on each other distort their orbits, which makes their distances from Jupiter vary. This, in turn, leads to changes in the shapes of the moons caused by the planet's tides. The result is continual flexing of the moons that, through friction, creates enormous amounts of internal heat.

Not surprisingly, this effect is strongest closest to Jupiter. Io is so intensely heated that active volcanos dot its surface. Gentler heating of Europa maintains a global ocean beneath the moon's icy crust. Ganymede's heating is currently negligible, but intense fractures visible on parts of its icy surface suggest this moon was warmer in the past. Only distant Callisto, an ice ball peppered with impacts, has escaped without any significant tidal heating.

Volcanic Io

Io is one of the solar system's strangest bodies. Unlike most other moons in the outer solar system, Io's surface and interior contain no ice. In this, the little moon resembles Earth, where a rocky mantle surrounds a large iron-rich core.

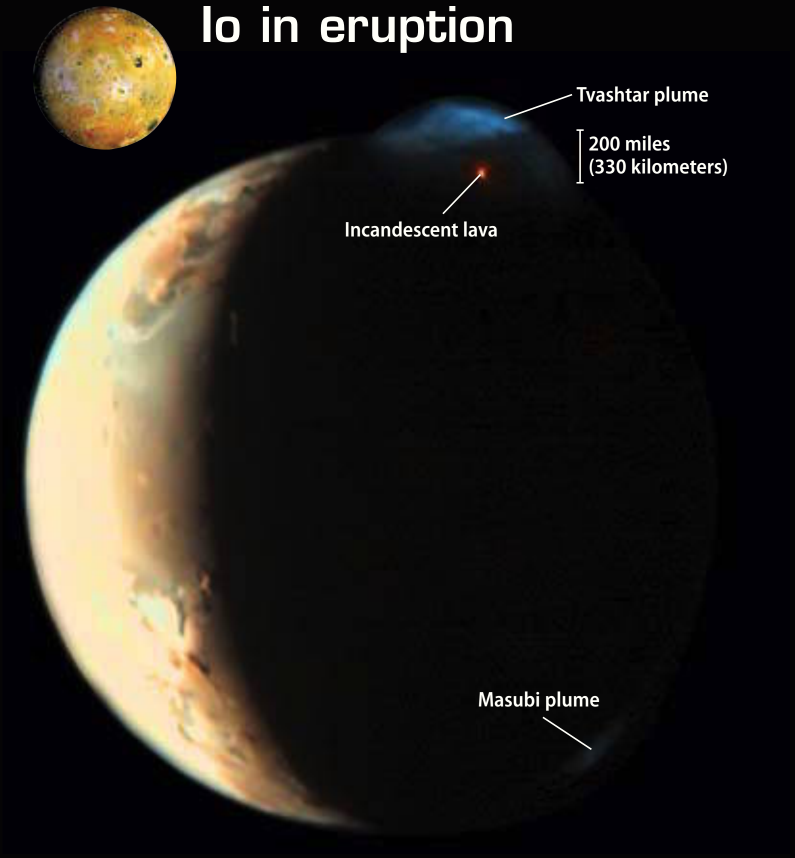
Io's surface displays a truly alien palette: orange, yellow, and brown sulfur give it the coloring of a pizza, with white sulfur dioxide providing highlights. Beneath this stark and garish paint job, though, lies dark, rocky lava. that may bear similarities to that which covers the Hawaiian Islands.

On Io, hundreds of volcanos are active at any given time. Some passively radiate heat as their lava cools; others violently explode, shooting debris plumes hundreds of miles into space.

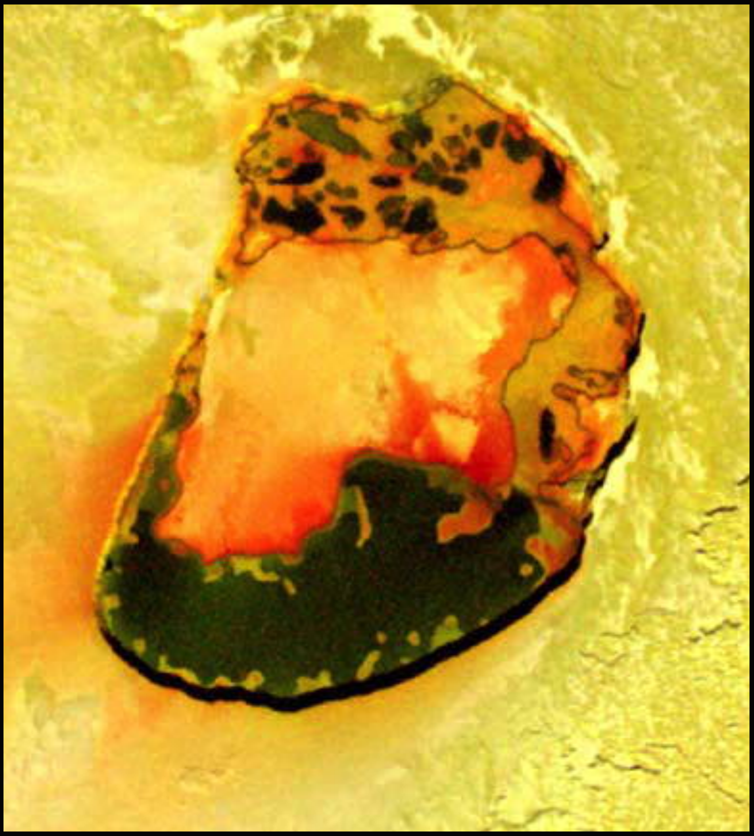
Some of the solar system's most dramatic mountains rise from Io's vast lava plains. The highest, Boosaule Mons, is roughly 55,000 feet (16,700 meters) high — almost twice the height of Mount Everest. Oddly enough, these mountains aren't volcanos. Planetary scientists think the most plausible explanation of their formation involves continuous piling up of surface lava. This causes downward pressure that eventually buckles the crust. The mountains then thrust upward.

Io has the most substantial atmosphere of any of Jupiter's moons — but it's still pretty tenuous, about one-billionth Earth's atmospheric pressure. Io's atmosphere is mostly made of sulfur dioxide gas emitted by the volcanos. The gas also freezes on the surface to form strange sulfur dioxide ice fields.

Io in eruption



▲ **A BRIGHT ORANGE** glow of hot lava punctuates the enormous blue plume from Io's Tvashtar volcano. Other plumes arc above the moon's dark limb. The New Horizons spacecraft captured the images in this composite in February 2007. JHUAPL/SWRI



▲ **TUPAN CALDERA,** a volcanic crater on Io, shows a rich palette thanks to interactions between molten rock and sulfur-rich materials. Black shows recent, still-cooling lava. Scientists believe yellow is a mix of sulfurous compounds. Green appears where red sulfur has interacted with the moon's dark lavas. Tupan is 47 miles (75 km) across and is surrounded by 3,000-foot-tall (900m) cliffs. Features as small as 443 feet (135m) can be seen in this image, which the Galileo orbiter captured in 2001. NASA/JPL/UNIV. OF ARIZONA

Europa, the ocean moon

Europa is as strange, in its own way, as neighboring Io. While mostly made of rock, with a central iron core, Europa's outermost layers are almost pure water. The water near the surface is frozen solid, but a few miles beneath this ice layer, it's likely that the water turns liquid. This global ocean may be 100 miles (161 kilometers) deep — a volume that dwarfs the total content of Earth's oceans.

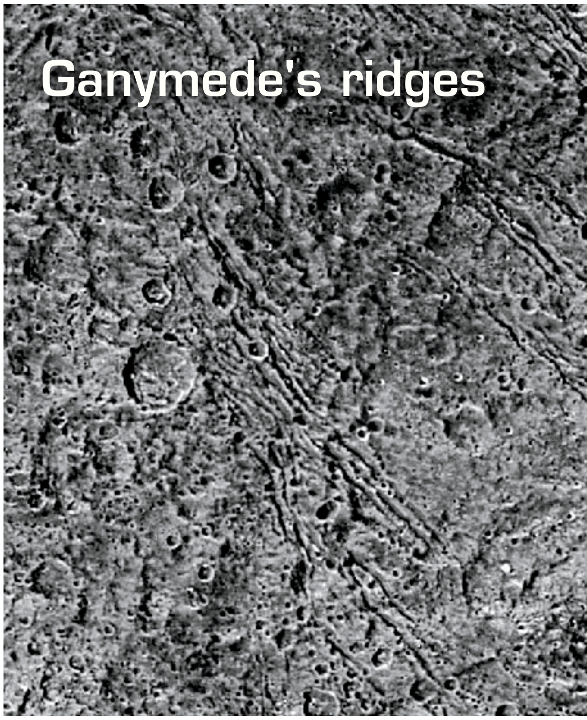
Fractures on all scales — the largest arc going around the globe — crisscross Europa's icy surface. For reasons that are still mysterious, many fractures run between a pair of ridges. These long double-ridges dominate much of the europan icescape, giving the moon the appearance of a ball of string.

Many of the fractures are straight, but others take the form of a series of connected arcs so geometrically precise that for many years they defied explanation. It now seems likely these strange arcs form when a fracture spreads across the surface in much the same way as a crack in a glass windshield gradually lengthens. In Europa's case, what guides the fracture's direction is Jupiter's rhythmically varying tidal pull.

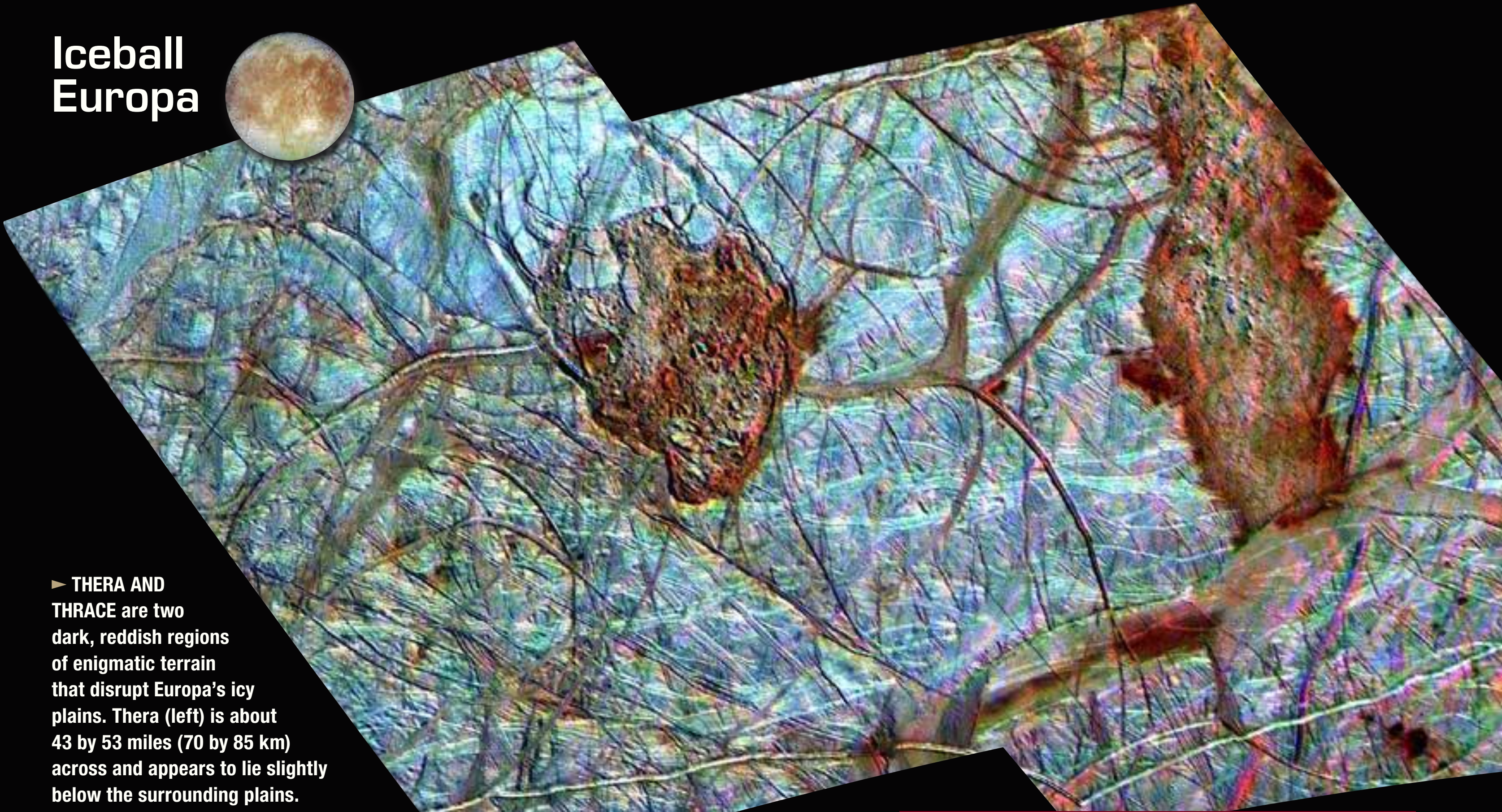
This process works only if the ice is weak and fractures easily, which is one of the reasons scientists think the ice is a thin, miles-thick shell overlaying an ocean. More direct evidence comes from magnetic-field measurements, which reveal an electrically conducting layer, most plausibly a salty ocean inside the moon.

Europa's apparent large amount of liquid water, a prerequisite for life, makes this moon one of the most promising known habitats for extraterrestrial biology. But it's not clear whether enough energy can reach the ocean to power a biosphere. Europa's surface is stained brown in many places by sulfur-rich salts or sulfuric acid that appear to have leaked onto the surface from the ocean below. A few small impacts gouge out clean ice and splash it across the surface, but they are few and far between.

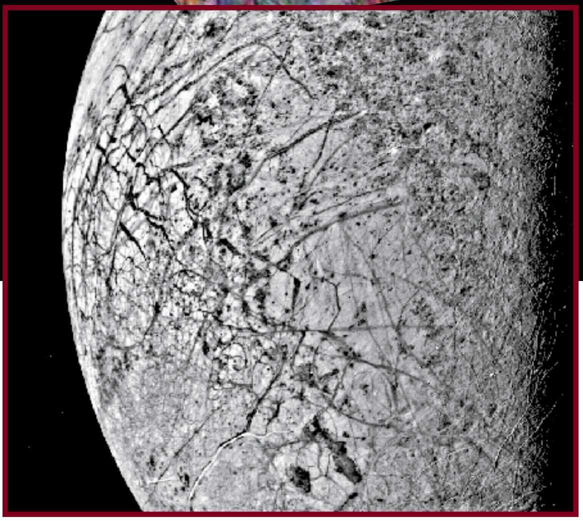
Ganymede's ridges



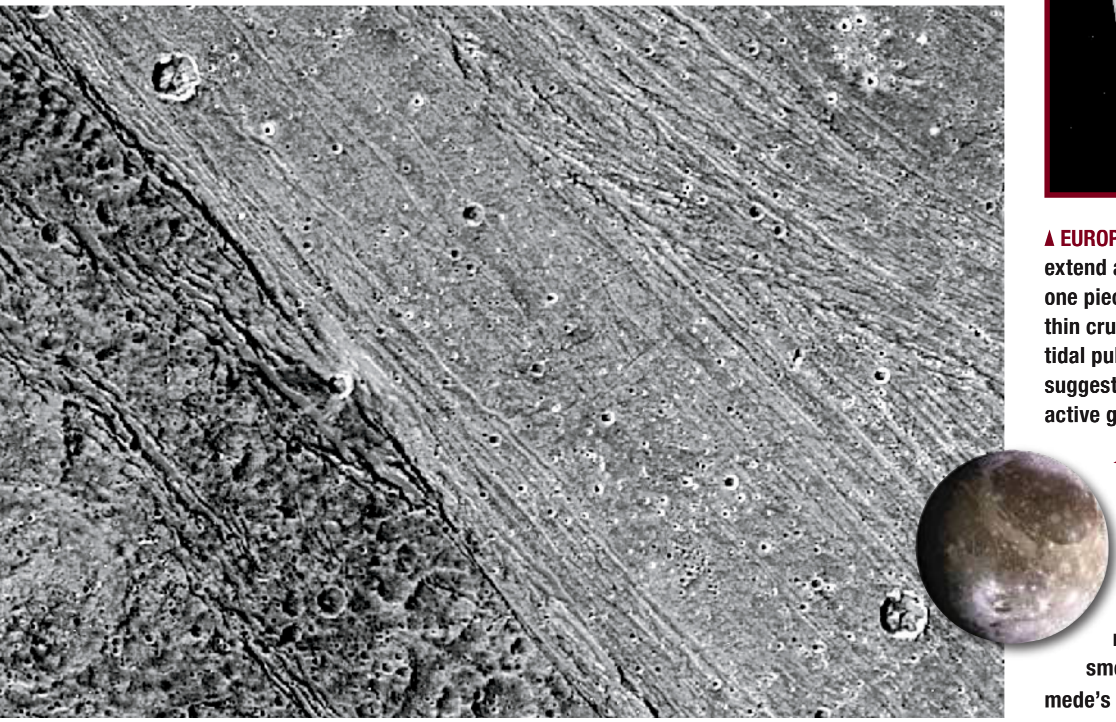
Iceball Europa



► **THERA AND THRACE** are two dark, reddish regions of enigmatic terrain that disrupt Europa's icy plains. Thera (left) is about 43 by 53 miles (70 by 85 km) across and appears to lie slightly below the surrounding plains. Curved fractures along its boundaries suggest Thera may have formed by collapse. By contrast, Thrace (right) is longer, shows a hilly texture, and appears to stand slightly above the bright plains. So-called chaotic terrain like Thera and Thrace may form when a subsurface ocean promotes melt-through of the moon's icy shell. Another possibility: Warm ice welling up from below partly melted the surface. NASA/JPL/UNIV. OF ARIZONA

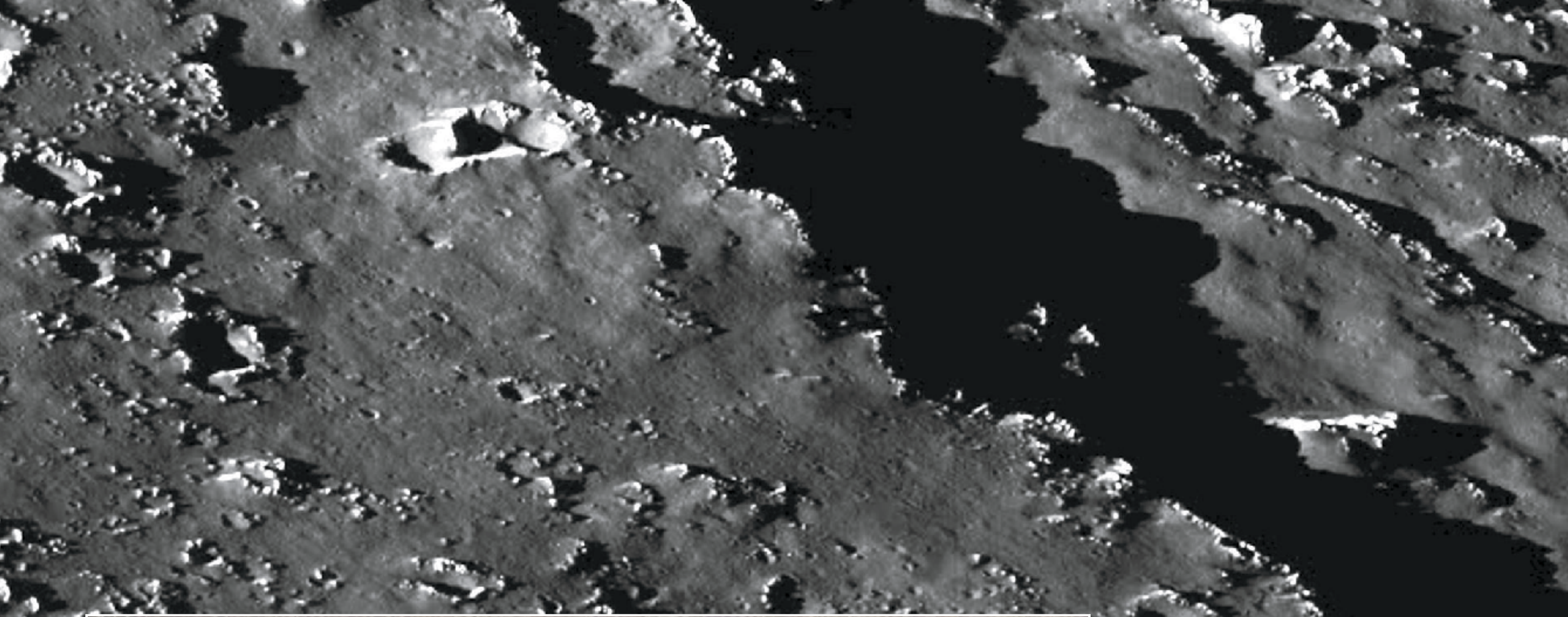


▲ **EUROPA'S ICY CRUST** contains puzzling fractures that often extend around the moon. The ice must crack easily, which is one piece of evidence that Europa hosts an ocean under a thin crust. The long fractures form in response to Jupiter's tidal pull. Few impact craters pock Europa's surface, which suggests the moon even now experiences some form of active geology that erases them. NASA/JPL

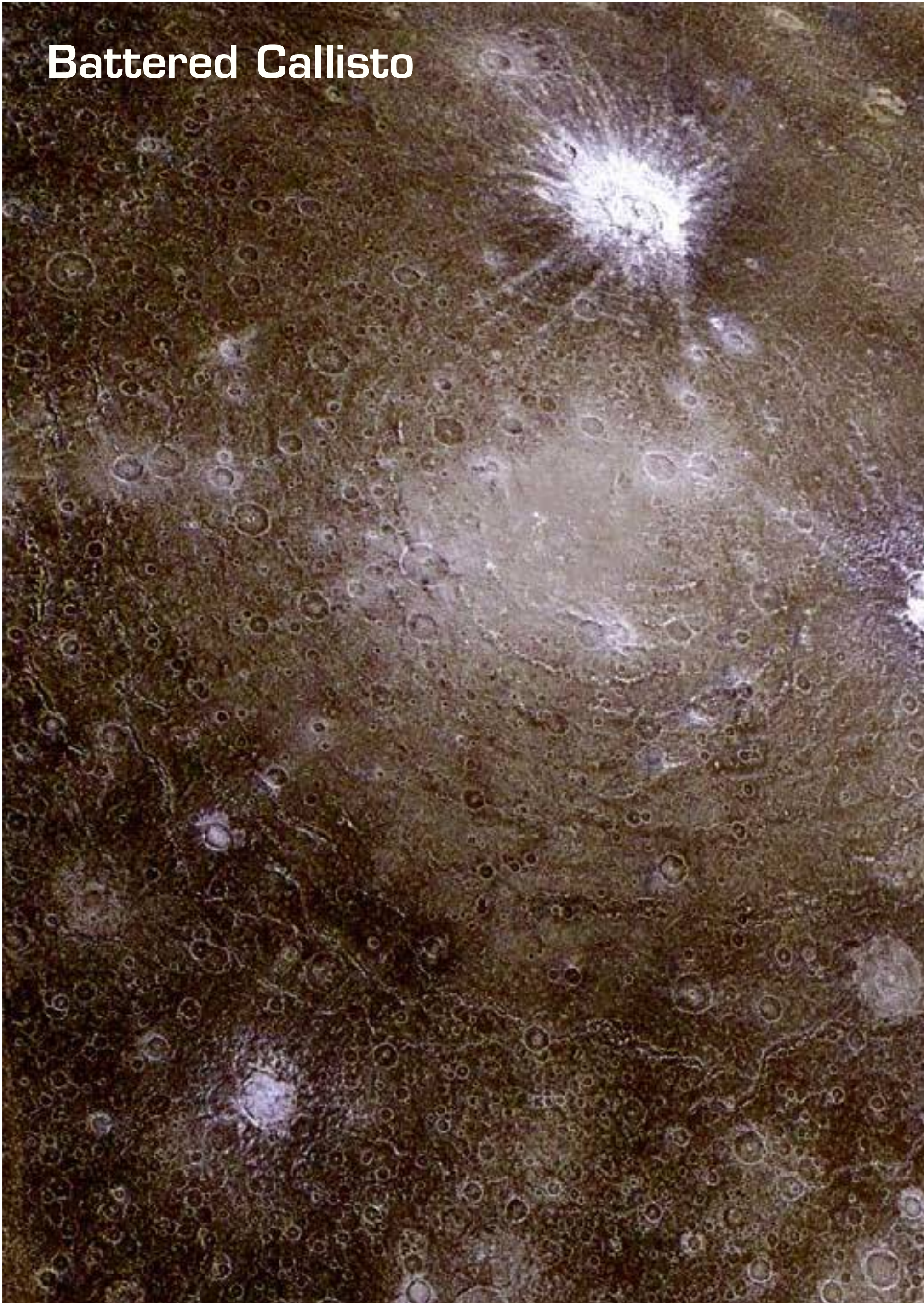


◄ **GANYMEDE** shows a sharp boundary between its two principal terrain types. The ancient, dark terrain of the moon's Nicholson Regio (left) contains lots of impact craters and fracture zones. The younger, brighter terrain of Harpagia Sulcus (right) has fewer craters and is relatively smooth. Subtle parallel ridges and grooves show that tectonic forces have smoothed out Harpagia Sulcus. Nevertheless, even Ganymede's youngest fractures are billions of years old. NASA/JPL/DLR

Battered Callisto



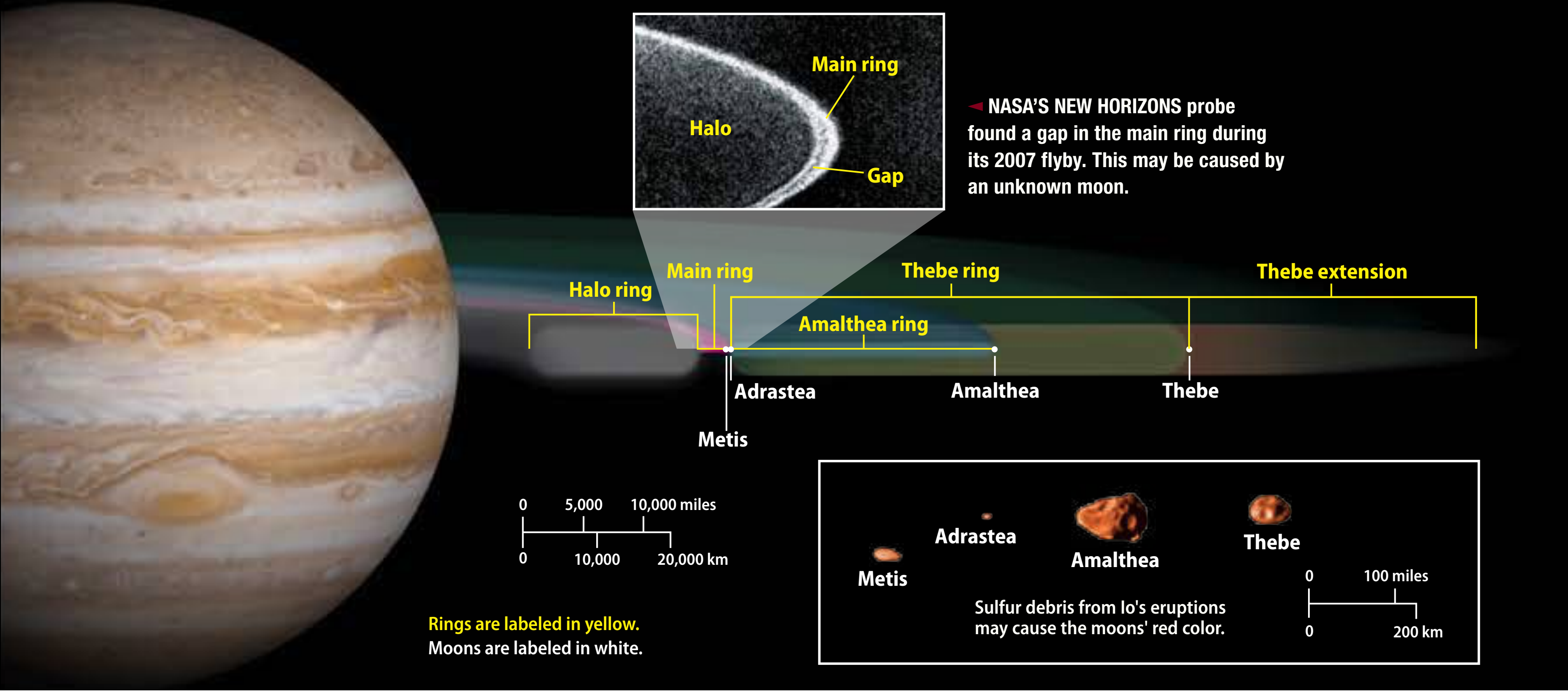
▲ **A PROMINENT FAULT SCARP arcs across Callisto. The feature is one of many structural components forming the moon's Valhalla multiring impact crater. A low Sun angle highlights the scarp's sharp drop. This image from the Galileo spacecraft covers a 20-mile (33 km) area and shows details as small as 150 feet (46m) across.** NASA/JPL/ASU



◄ **CALLISTO'S ASGARD impact structure gives the moon an unmistakable bull's-eye. Concentric rings up to 1,050 miles (1,700 km) across surround the ancient impact site. The icy materials excavated by younger craters contrast sharply with the darker, redder coatings on Callisto's older surfaces. The bright young crater named Burr (top) partially obscures a second multiring impact structure about 310 miles (500 km) across.** NASA/JPL/LPL/UNIV. OF ARIZONA

A giant's ghostly rings

THIS PLOT shows the size and locations of Jupiter's innermost moons and tenuous dust rings. *ASTRONOMY*: ROEN KELLY



◄ **NASA'S NEW HORIZONS probe found a gap in the main ring during its 2007 flyby. This may be caused by an unknown moon.**

Rings are labeled in yellow.
Moons are labeled in white.

Sulfur debris from Io's eruptions may cause the moons' red color.

That's an indication Europa's surface is quite young — only a few tens of millions of years old — and that the geological reworking of its icy crust probably continues to this day.

Groovy Ganymede

Ganymede is Europa's more sedate big brother. It's larger than the planet Mercury (although much less massive) and is the biggest moon in the solar system. Ganymede's surface is ice-rich like Europa's, but on Ganymede, the ice layer makes up half the moon. Beneath the ice lie rock and a central iron core.

Parts of the surface are intensely fractured, but, Ganymede's style differs from Europa's. Rather than Europa's crisscrossing double ridges, Ganymede sports long ribbons of parallel fractures that cut pale swaths through older, darker, cratered landscape. Even the fractured regions contain heavy cratering.

Many comets and asteroids have crashed into Ganymede's surface since its active geology slowed to a stop. Researchers say even the fractured terrain is a couple of billion years old. However, some leftover energy source warms and stirs Ganymede's iron core, generating a substantial magnetic field that distinguishes Ganymede from all other planetary satellites.

Iceball Callisto

Callisto is almost as big as Ganymede and similar in composition: equal parts rock and ice.

Paradoxically, what makes Callisto most interesting is its lack of interesting features. The moon hasn't experienced the tidal heating that so affected the other Galilean moons — no fractures, volcanos, or other signs of internal activity disturb its surface.

Instead, Callisto's landscape is dominated by endlessly overlapping impact craters. This is a sure sign Callisto has experienced little except the occasional interplanetary crash since shortly after the solar system formed. The largest of these impact scars is a giant bull's-eye of concentric ridges more than 1,200 miles (1,930 km) across. Callisto has remained so cold throughout its history, the rock within it never had a chance to separate from the ice and sink to the center. Most of Callisto's interior seems to be an undifferentiated ice-rock jumble.

Inner moons and rings

Inside the orbit of Io, close to Jupiter itself, orbit four much smaller moons: Adrastea, Metis, Amalthea, and Thebe. The largest, potato-shaped Amalthea, is only 155 by 80 miles (250 by 129 km) in size. None of these moons is large enough for gravity to pull it into a spherical shape, but each is remarkable for the delicate rings it creates and controls.

The rings are insubstantial compared to Saturn's mighty system, but they're fascinating in their own right. Dust chipped off the moons by impacts seems to be responsible for the rings. The main jovian ring is sandwiched between the orbits of Adrastea and Metis, but a faint sheet of dust extends inward toward the planet's cloud tops. Magnetic forces puff up the dust sheet as it approaches the planet. The dust particles pick up an electrical charge under the intense bombardment from energetic ions near Jupiter and respond to the magnetic field.

Amalthea and Thebe also shed dust and generate their own rings. But their creations are even more tenuous than the main ring.

A hive of outer moons

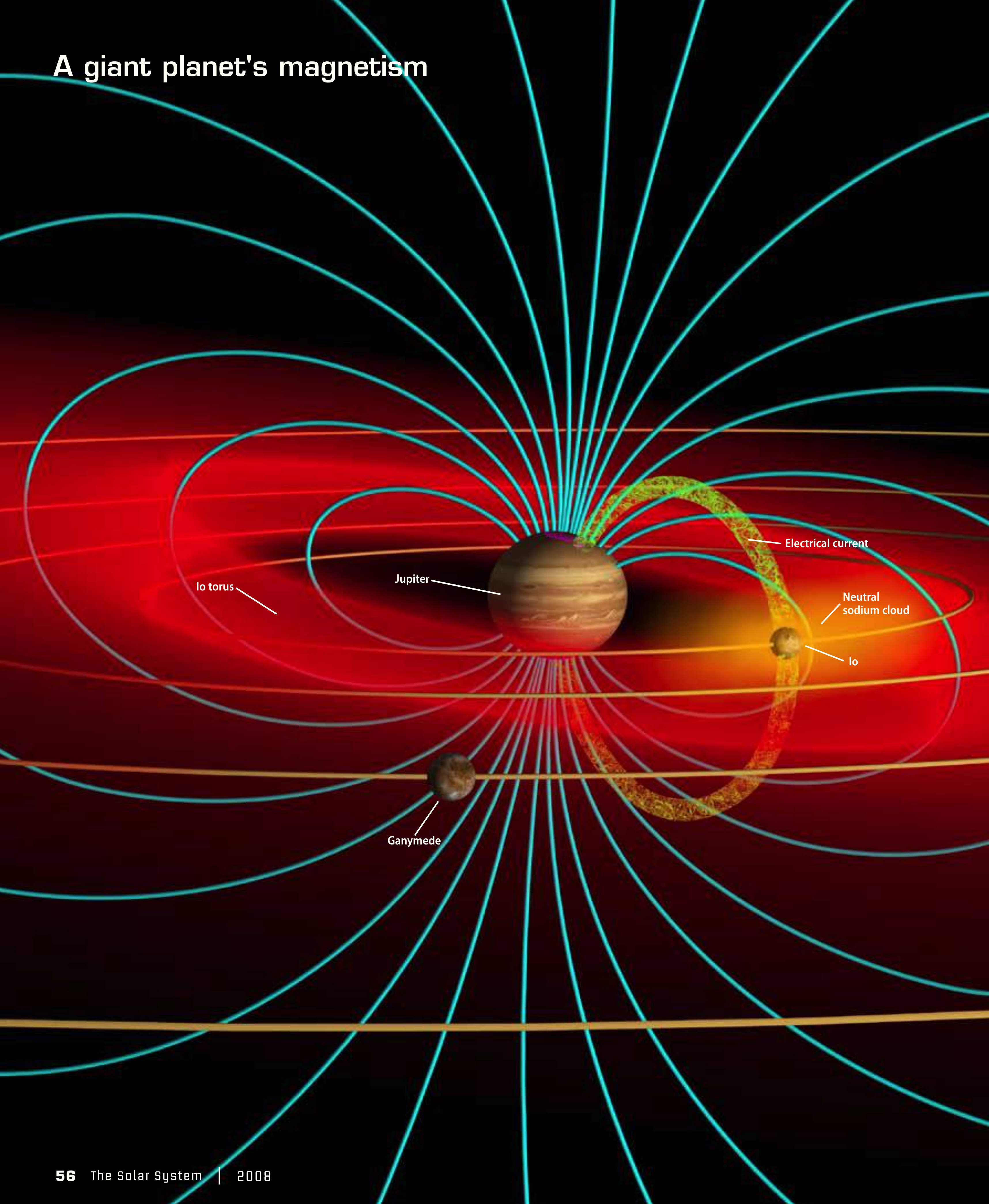
Most of Jupiter's moons lie much farther from the planet. Ranging from 100 miles (161 km) across to just a few miles in size, the 55 known outer moons comprise several sets of objects with similar orbits. Some of them orbit the planet in the opposite direction of its rotation and those of the closer moons.

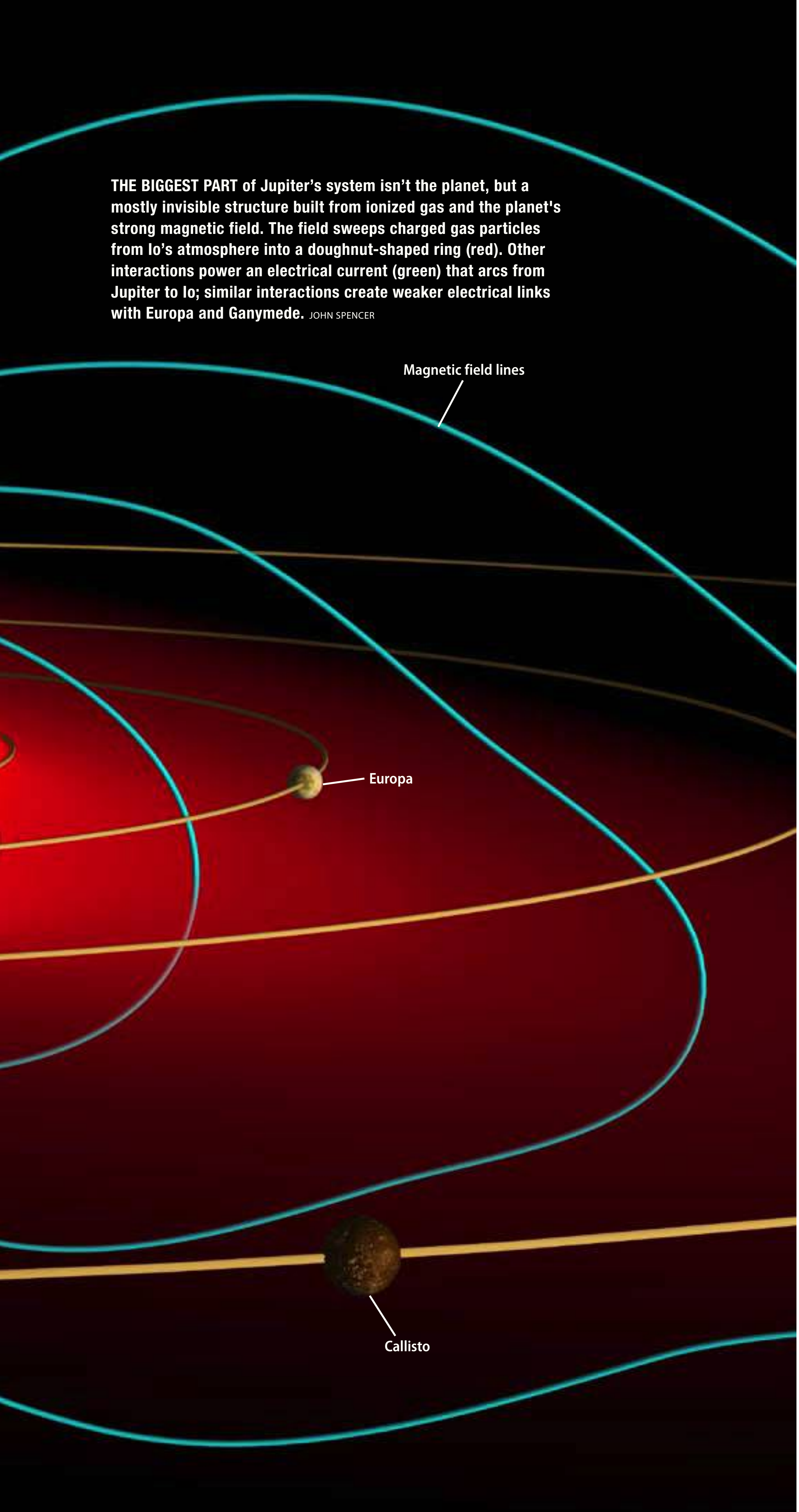
It's likely these moons are interplanetary debris that Jupiter captured early in its history. Each set of moons on similar orbits is thought to be a swarm of fragments from a single larger moon that collisions broke apart. Because astronomers discover more of these outer moons all the time, their total count likely exceeds 100.

Giant magnetosphere

The biggest part of the Jupiter system is not the planet itself, but its enormous magnetosphere.

A giant planet's magnetism


Electrical current
Io torus
Jupiter
Neutral sodium cloud
Io
Ganymede



THE BIGGEST PART of Jupiter's system isn't the planet, but a mostly invisible structure built from ionized gas and the planet's strong magnetic field. The field sweeps charged gas particles from Io's atmosphere into a doughnut-shaped ring (red). Other interactions power an electrical current (green) that arcs from Jupiter to Io; similar interactions create weaker electrical links with Europa and Ganymede. JOHN SPENCER

STATISTICS: Jupiter vs. Earth

	Jupiter	Earth comparison
Mass	4,186 trillion trillion pounds	318 times Earth's mass
Diameter	88,846 miles	11 times wider
Density	1.33 grams/cc	24.0%
Weight of 150-lb person	380 pounds	2.5 times Earth's weight
Distance from Sun	483.8 million miles	5.2 times farther
Orbital period	11.86 years	11.9 times longer
Length of day	9.926 hours	41.4%

Mass: Total mass (1 trillion = 10^{12}); **Diameter:** Equatorial diameter; **Density:** Average density in grams per cubic centimeter (water = 1); **Distance from Sun:** Average distance; **Orbital period:** Sidereal period; **Length of day:** Average time between successive noons; **Earth comparison:** Ratio of Jupiter's to Earth's value.

This bubble of plasma is larger than the Sun and anchored in place by the planet's powerful magnetic field. Near Jupiter, where the magnetic field is strongest, the plasma becomes locked to the planet's rotation and rotates once every 10 hours. In its outer reaches, the magnetosphere is warped and buffeted by the solar wind and streams away from the Sun to form a "magnetotail." This may extend to Saturn's orbit.

Sulfur and oxygen ions supplied by Io's volcanos make up most of the plasma. The material escapes the moon's atmosphere to form a dense ring of glowing gas, called the Io torus, around the moon's orbit. From there, the plasma spreads throughout the magnetosphere, bombarding the other moons and producing the most hostile radiation environment known around any planet.

Some of these ions channel along the magnetic field to Jupiter's poles, where they bombard the upper atmosphere and generate complex and dramatic auroral displays. A direct magnetic connection between Io and Jupiter produces a glowing spot at the point where the magnetic field line connected to Io touches the jovian atmosphere. Europa and Ganymede produce similar, fainter spots of their own. These auroral spotlights slowly march around Jupiter at the pace of their moons' orbits as the planet rotates beneath them.

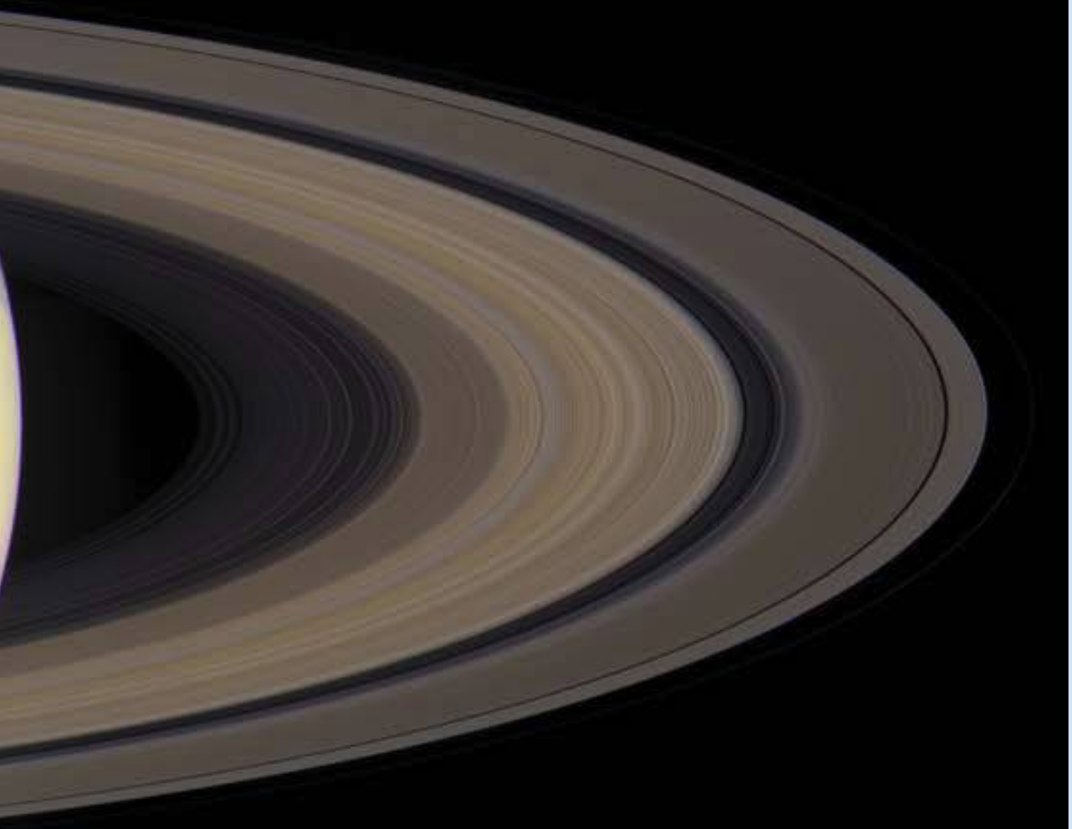
Jupiter isn't just a planet. It's a wonderfully dynamic, diverse, and interconnected system. We've learned much through telescopes and spacecraft, but many surprises remain. The solar system's largest world remains a compelling target for future exploration. The next space mission destined for Jupiter is NASA's Juno spacecraft, slated to settle into orbit around the planet in 2016. What wonders it will discover, we can only guess. ◘

Solving mysteries of the great ringed

world

New data from the Cassini-Huygens mission reveal astonishing details about Saturn's complex rings and exotic moons.

by Bill McKinnon



REFLECTED LIGHT from Saturn's ring system illuminates the planet's night side. NASA's Cassini orbiter continues to beam similarly magnificent portraits back to Earth, deepening scientists' understanding of Saturn and its many moons. NASA/JPL/SSI

O wondrous, ringed world! And Saturn is indeed a wonder. Its ornamentation of rings and moons makes it the crown jewel of the eight major planets. Saturn never fails to astonish the first-time telescope viewer, nor has it ceased to intrigue astronomers.

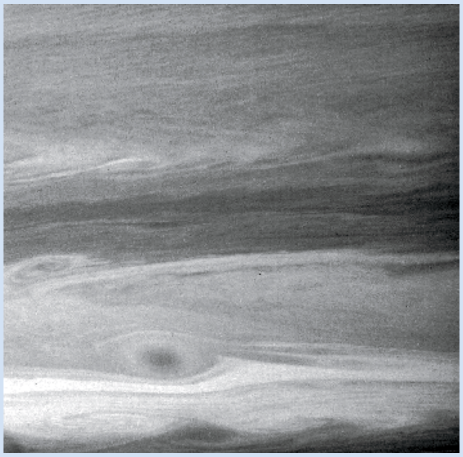
Our knowledge of the ringed giant has grown exponentially since June 2004, when the Cassini-Huygens mission arrived at Saturn. The spacecraft has revealed new insights into the structure and origin of Saturn's ring system. We've touched down on the surface of Saturn's largest moon, Titan, and marveled from orbit at the liquid methane lakes and river drainage networks of this "new Earth." Saturn's exotic moons, too, have never failed to surprise — most notably, Enceladus' more than 100-mile-high (160 kilometers) geysers.

Despite all Cassini-Huygens has done to deepen our understanding of Saturn, these accomplishments have only whetted scientists' appetites for more data. And Cassini remains on the job more than 4 years after entering orbit around Saturn in June 2004.

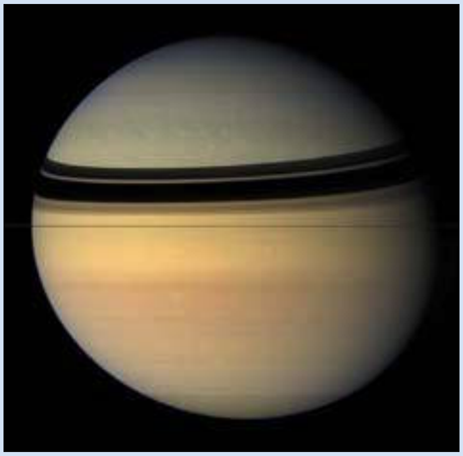
Although the Cassini-Huygens mission continues, planetary scientists have begun the

Bill McKinnon *is a planetary scientist at Washington University in St. Louis. His research focuses on the outer solar system's icy satellites and Kuiper Belt objects, and the physics of impact cratering.*

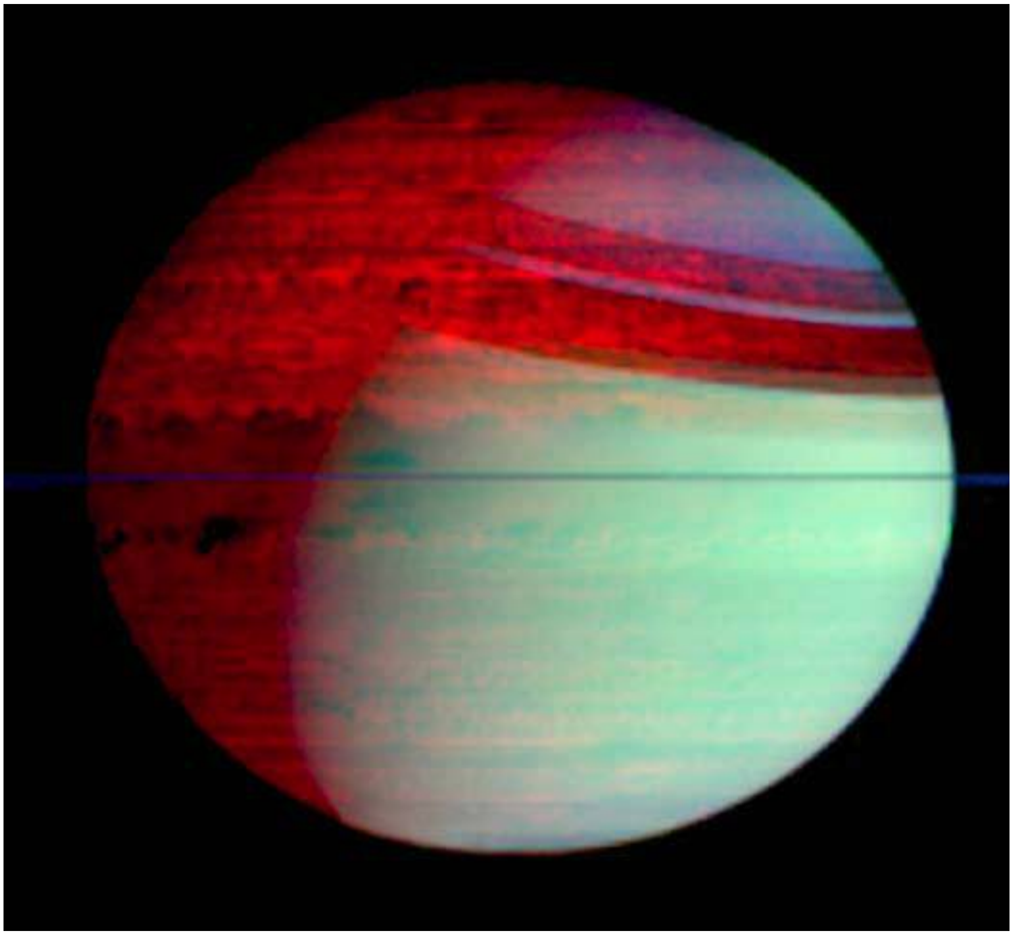
▲ **FAST-MOVING WINDS** in Saturn's atmosphere form distinct belts. High cloud layers contain mostly ammonia ice. Bright clouds dot the southern polar region. NASA/JPL/SSI



▲ **BETWEEN WIND STREAMS** blowing in opposite directions, eddies form massive cyclonic gales resembling terrestrial hurricanes. NASA/JPL/SSI



▲ **TO REVEAL SATURN'S NATURAL COLORS,** Cassini imaged the planet through red, green, and blue filters. The blue hue of the northern hemisphere stands out against the yellow tones of the planet's equatorial zone. NASA/JPL/SSI



▲ **CASSINI'S IMAGING SCIENTISTS** used the craft's Visual and Infrared Mapping Spectrometer to capture Saturn's deep clouds silhouetted against emissions (in red) from the planet's still-hot interior.

NASA/JPL/UNIVERSITY OF ARIZONA

advanced planning for the next great missions. NASA and the European Space Agency (ESA) could launch another orbiter with probes to Saturn late in the next decade.

Astonished and perplexed

Even through primitive telescopes, Saturn astonished observers — and perplexed them, too. Italian astronomer Galileo Galilei (1564–1642), describing his 1610 telescope observations of Saturn, wrote, "I have observed the most distant planet to be a triple one."

Galileo interpreted the "triple one" to be a planet with two attendant satellites. But unlike the moons of Jupiter, the "lesser Saturnian stars" did not move with respect to the planet, were located symmetrically on either side of Saturn, and, over the years, disappeared entirely — and then reappeared!

Decades of ever-improving telescopic observations did not solve the "Saturn problem" until 1655. The Dutch astronomer Christiaan Huygens (1629–1695) discovered Saturn's first true moon, Titan — also its largest. The geometry of its orbit provided the key to interpreting what had by then become known as "ears" or "handles" (in Latin, *ansae*). He described Saturn as "surrounded by a thin, flat ring, nowhere touching." The nature of this ring — whether solid, or fluid, or something else — would not be worked out for another 2 centuries.

Considering what these early observers of Saturn confronted — a sight unlike any seen before — their interpretations are all the more remarkable. We live in similarly ingenious times, and have sent robots to observe Saturn and its rings and moons up close.

The NASA Cassini orbiter and the ESA and Italian Space Agency's Huygens lander, which touched down on Titan in January 2005, came decades after visits by Pioneer 11 (1979), Voyager 1 (1980), and Voyager 2 (1981).

Welcome to Saturn

We have learned much about Saturn in the last 400 years. To the ancients, it was the outermost planet. Because of its distance — 8 astronomical units (AU), or 750 million miles at its minimum distance from Earth — it's easy to forget Saturn is truly a giant planet. Its equatorial girth measures 74,900 miles (120,500 kilometers), or 9.5 times wider than Earth's.

Saturn weighs about 95 Earth-masses, second only to Jupiter. Because of its great size, yet comparatively modest mass, Saturn's density is only 69 percent of water's. That means it's the least dense of the planets. In fact, it would float if placed in a giant tub of water.

Saturn is made primarily of hydrogen (H) and helium (He), just like Jupiter and the Sun. The abundance of these gases accounts for Saturn's comparatively low density. Coupled with a rapid rotation (once every 10.6 hours), Saturn is manifestly oblate, or about 10-percent wider at its equator than at the poles.

Core values

But appearances can be deceiving. Deep inside Saturn lies a condensed core of heavy elements other than hydrogen and helium. Under normal pressures and temperatures, the heavy elements would form rock, metal, and ice. We can only guess at the arrangement and properties of the matter at Saturn's center. One thing is certain: Given the high temperatures and pressures, there must be plenty of dense, exotic matter down there — some 10 to 20 Earth-masses of the stuff.

Details of Saturn's gravity field indicate the planet has the most compact core of any of the solar system's planets or moons. The core is so well defined, it is the best evidence we have that both Jupiter and Saturn formed by a process called core accretion-gas capture.

In this process, a mass of heavy elements forms within the disk-like primordial nebula encircling the young Sun. When the core grows massive enough, its gravity attracts increasing amounts of hydrogen and helium gas. This process eventually culminates with formation of a gas-giant planet.

Deep inside Saturn, hydrogen gas is so compressed that it transforms into a liquid metal. As the metal churns, enormous electric currents create a powerful magnetic field.

Saturn's surface magnetic field strength is two-thirds of Earth's, but the reach of this field is much greater, creating a vast magnetic envelope or magnetosphere around the planet. Charged particles from either the solar wind or derived from the planet, its rings, or its moons populate the magnetosphere. The interaction of these particles with Saturn's magnetic field creates familiar and beautiful phenomena, such as aurorae at Saturn's poles.

Weather report

Saturn can change its colors. Most of the time the orb is a light butterscotch. This is due, at least in part, to tiny hydrocarbon droplets (aerosols) produced by ultraviolet (UV) radiation acting on the atmosphere high above Saturn's visible clouds. Saturn's atmosphere is relatively rich in methane, providing an abundant supply of hydrocarbon "feedstock" to produce aerosols.

Saturn's winter hemisphere points 27° away from the Sun. The rings also shade the surface during winter. So, when Cassini scientists found that Saturn's northern (winter) hemisphere had turned blue, they were thrilled. The yellowish haze diminished to the point that Saturn's winter atmosphere was more like Earth's in the way it scatters blue light.

Most of the year, however, the aerosol haze on Saturn is thick and masks the underlying cloud patterns. Judicious use of filters and digital processing to highlight features in Cassini images nevertheless reveals that the weather patterns on Saturn are nearly as dynamic and active as Jupiter's.

A great leap downward

A skydiver plunging through Saturn's atmosphere would first descend through a yellowish haze of ammonia-ice crystals, then emerge into relatively clear air, only to plunge back into a cloud of ammonium-hydrosulfide-ice particles. The clouds would thicken and then their contents would shift abruptly to water ice. Just as temperatures become "tolerable," the water-ice particles would become ordinary water drops — albeit with a strong scent of ammonia.

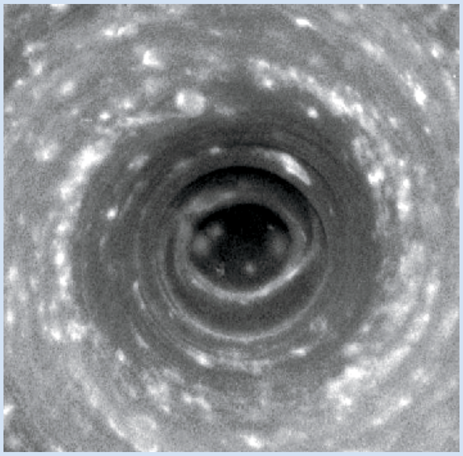
No parachute would be necessary for such a dive. In Saturn's dense atmosphere, a skydiver's velocity would decrease steeply with increasing depth, although a breathing apparatus would be a good idea. The temperature and atmospheric pressure would also increase continuously.

Depending on the latitude chosen, a skydiver could experience fierce side winds. Voyager images indicated a broad equatorial jet whose maximum speed reached well over 1,000 mph (1,600 km/h), although Cassini has not yet confirmed this super "jet stream" speed.

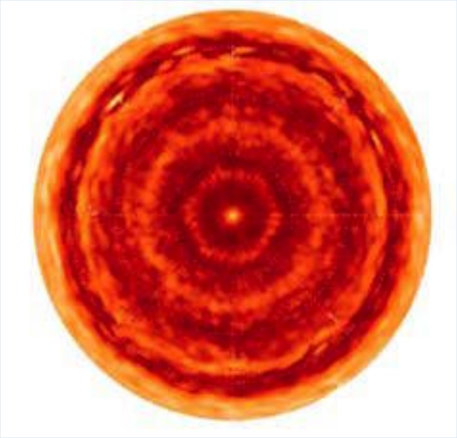
A skydiver at the south pole would experience something quite different. Cassini images show a hurricane-like vortex centered precisely on the pole. The vortex sports an "eye wall" similar to those in terrestrial hurricanes, and multilevel cloud decks arranged in a stair-step pattern. Skydiving there would be a one-way trip, but what a view on the way down!

Rings of wonder

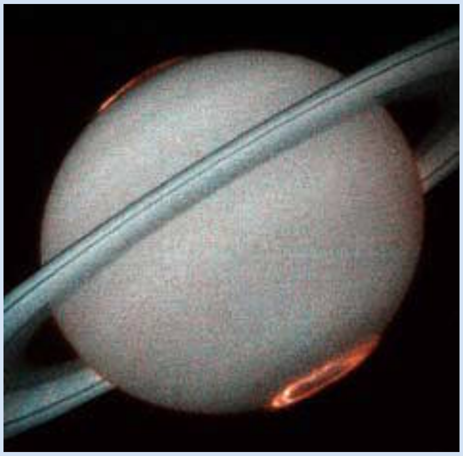
For most people, Saturn's magnificent ring system is what truly makes the planet special. In 1675, Italian-French astronomer Giovanni Cassini (1625–1712) discovered a distinct gap indicating two major rings, not just one. This



▲ **IN THE SOUTH POLE'S "EYE OF KRONOS," winds blow counterclockwise at 350 mph (550 km/h) The eye's wall reveals multiple cloud layers, or "decks," in Saturn's turbulent atmosphere.** NASA/JPL/SSI

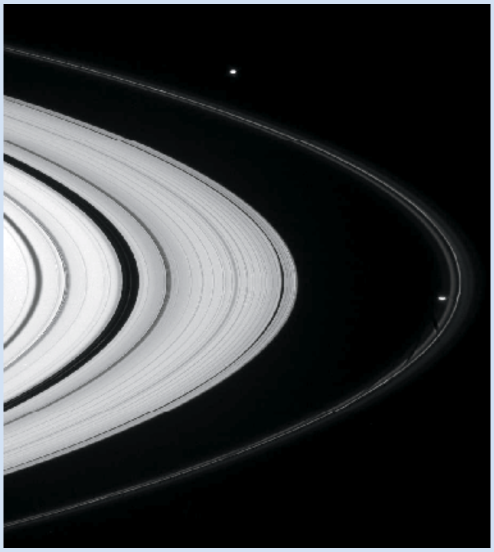


▲ **A HEXAGONAL "HOT SPOT" PEERS OUT from Saturn's north pole. Temperatures at the polar eye range from –330° to –310° Fahrenheit (–201° to –190° Celsius).** NASA/JPL/GSFC/OXFORD UNIVERSITY

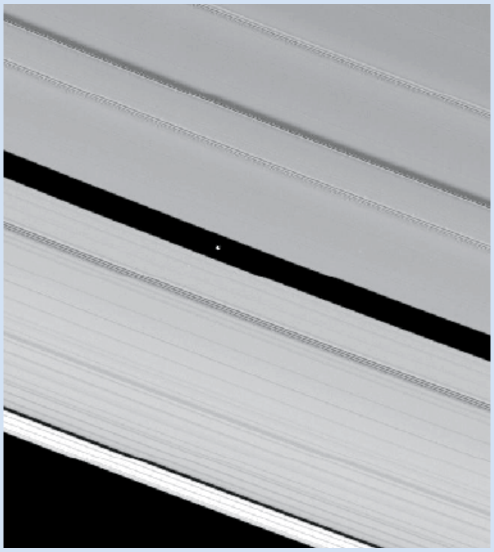


▲ **POWERFUL MAGNETIC FIELDS cause auroral rings to erupt at Saturn's poles in this rare view snapped in 1997 by the Hubble Space Telescope. Methane in Saturn's atmosphere absorbs virtually all ultraviolet light, rendering most of the planet's surface a dull gray.** J. T. TRAUGER (JPL)/NASA

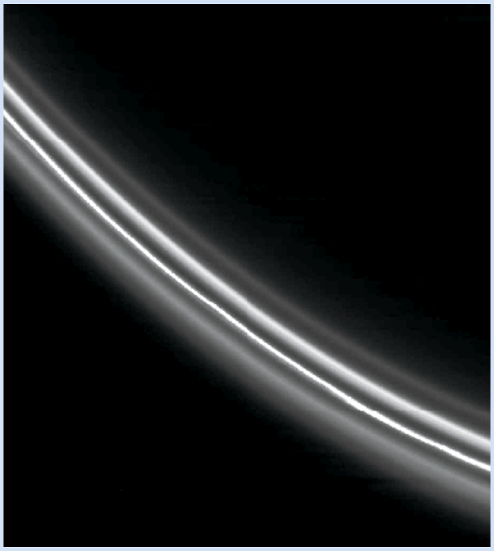
SATURN and its rings are backlit in this mosaic of deep exposures designed to detect sunlight scattered from small particles. The effect is similar to the diffuse light scattered from smoke in a nightclub. NASA/JPL/SSI



▲ **"SHEPHERD MOONS"** sculpt Saturn's rings with their gravitational influence. In this image, the moons Prometheus and Pandora orbit inside and outside, respectively, Saturn's narrow F ring. NASA/JPL/SSI

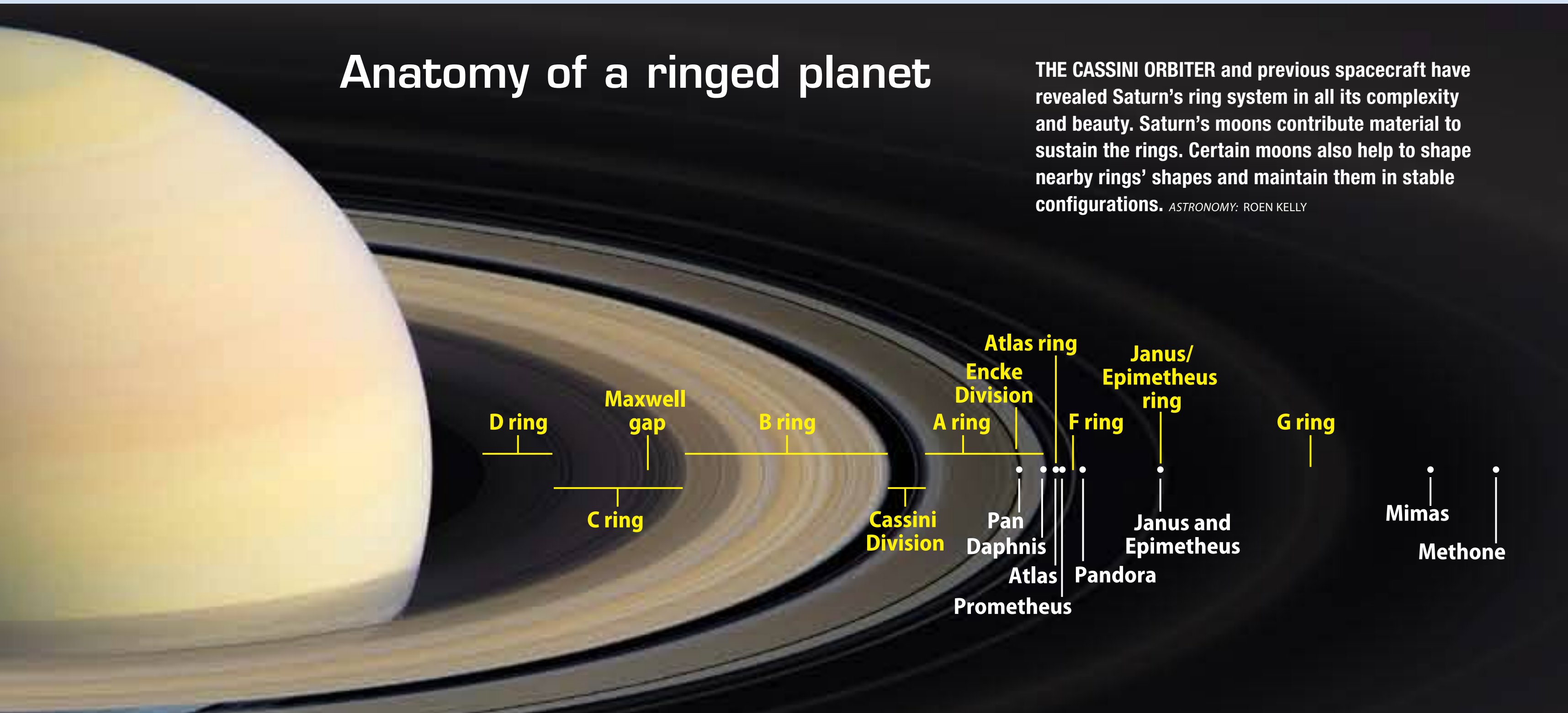


▲ **EVEN TINY DAPHNIS,** only 4.3 miles (7 km) across, can induce waviness in the edge of the Keeler Gap. The gap lies within the A ring, about 150 miles (250 km) from the ring's outer edge. NASA/JPL/SSI



▲ **CASSINI OBSERVATIONS** suggest that gravitational tugs from Saturn's moon Prometheus create subtle bends or "kinks" in the F ring. Dimmer, smoother ringlets flank the brighter, denser F ring. NASA/JPL/SSI

Anatomy of a ringed planet



THE CASSINI ORBITER and previous spacecraft have revealed Saturn's ring system in all its complexity and beauty. Saturn's moons contribute material to sustain the rings. Certain moons also help to shape nearby rings' shapes and maintain them in stable configurations. *ASTRONOMY:* ROEN KELLY

D ring
Maxwell gap
B ring
C ring
Cassini Division
A ring
Encke Division
Atlas ring
F ring
Janus/ Epimetheus ring
G ring
Pan
Daphnis
Atlas
Prometheus
Pandora
Janus and Epimetheus
Mimas
Methone

theme has continued ever since, with gaps and divisions, wide rings and narrow ringlets, and sharp or diffuse ring edges, proliferating to the limit of resolution.

The rings contain billions of reflective particles. Each behaves like a micro-moon following an independent circular orbit around Saturn. The ring particles jostle and bump into one another, dissipating energy so as to maintain a ring of remarkable thinness — no more than 330 feet (100 meters) thick on average. In some cases, pairs of "shepherd moons," orbit along each side of a ring. Their gravitational influences maintain the ring's shape.

The system also includes "ring moons," which orbit in the gaps between rings. The ring material bends and ripples in response to gravitational tugs by the moons, forming wavy patterns. The gravity-driven physics of the rings is rich and baffling, although certain details of the process are now understood.

Observations from ground-based telescopes and spacecraft indicate that particles in the main A, B, and C rings are composed of nearly pure water ice and measure from millimeters to meters in width. The Cassini orbiter discovered some as large as 300 feet (90m). More tenuous rings exist outside the main system, including one (the E ring) associated with the satellite Enceladus. These outer rings contain the finest particles in the system.

The rings' origin remains a great mystery. They may be remnants of the nebular disk from which the moons originally formed. Or, they may be fragments of a former moon that broke up catastrophically, due either to Saturn's gravitational tides or a comet impact.

The rings and their companion moons are dynamic. Many planetary scientists suspect what we see today is just a snapshot, astronomically speaking. In particular, at locations in the rings where the orbital period of a particle is a simple fraction of the orbital period of an external moon, gravitational interactions called resonances shape the rings.

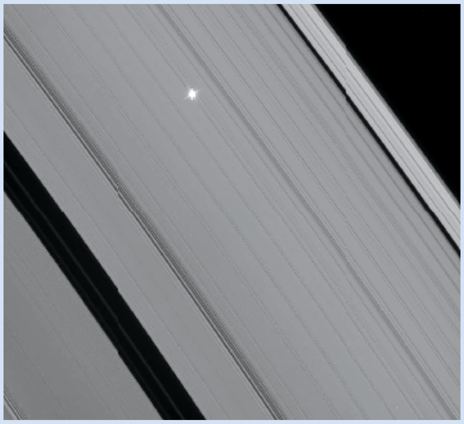
As an example, the outer edge of the B ring is in a 2:1 resonance with the midsize icy moon Mimas. A 7:6 resonance with 110-mile-wide (180 km) Janus maintains the A ring's outer edge. But what happens if Janus is destroyed by collision with a high-speed comet? (It already appears to have split in two, sharing its orbit with a partner, Epimethius.) Does the A ring spread outward like a swarm of angry bees? Does the entire ring system rearrange? All we can say at present is that millions of years from now, the rings will probably look very different.

The satellite collector

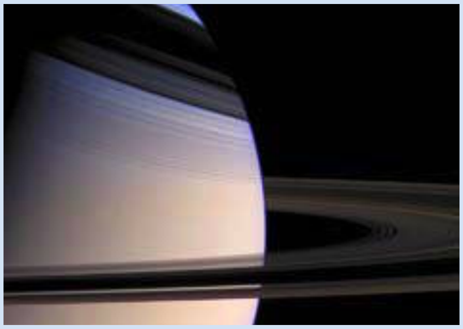
Saturn's satellites comprise a diverse population. They range in size from minuscule (the ring particles) to enormous — for example, Titan, the solar system's second-largest moon. Ring particles aside, the satellites are uncountable.

Beyond the so-called regular moon system lies a swarm of "irregulars" with eccentric and inclined orbits. Some of them travel in the same direction as Saturn's spin, while others circle in the opposite direction.

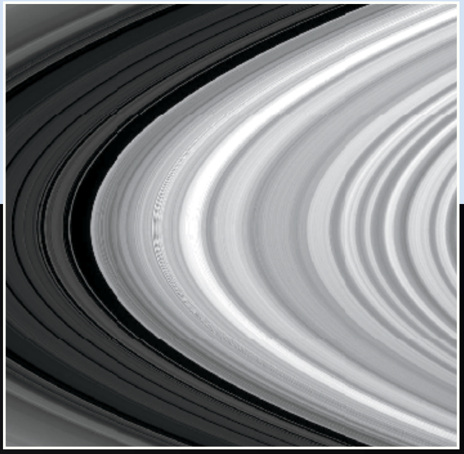
The irregulars don't seem to fit in. They were probably captured from the Kuiper Belt, a major source of comets. As of this writing, the total number of individually identified satellites stands at 60. But probably not for long.



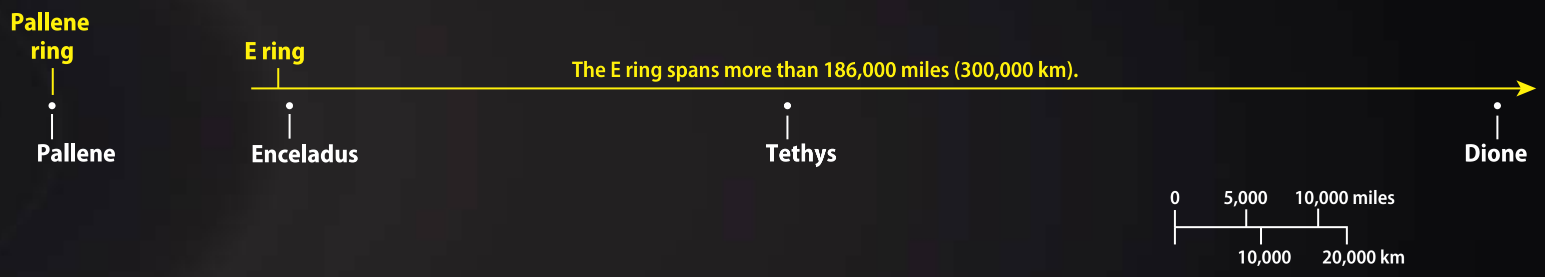
▲ ANTARES, THE BRIGHTEST STAR in Scorpius, sparkles behind Saturn's rings, betraying their thinness. NASA/JPL/SSI

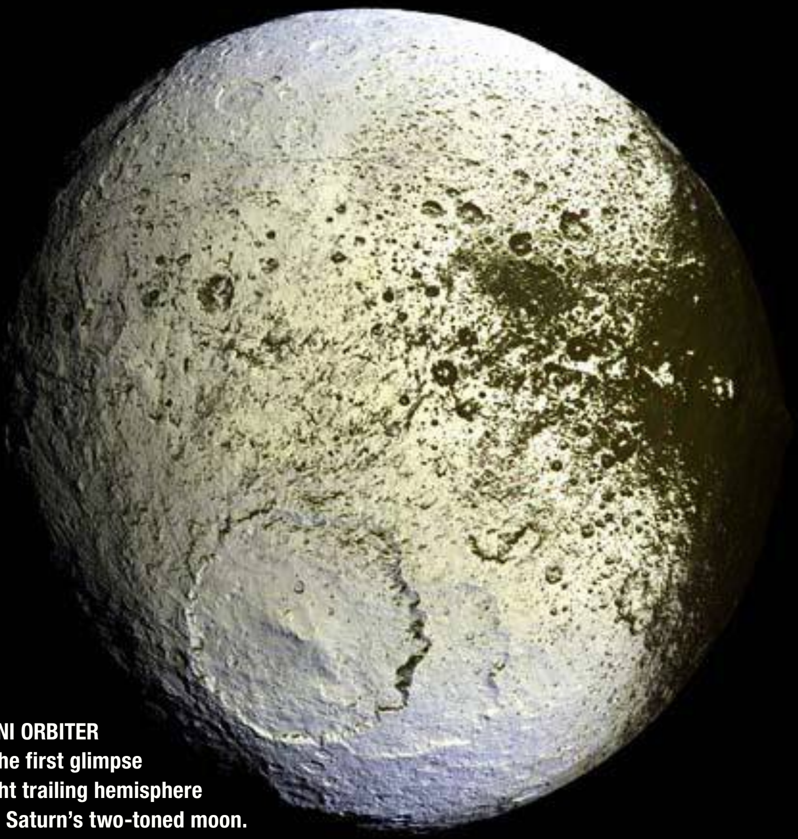


▲ IN THIS CASSINI PORTRAIT, Saturn's north pole points away from the Sun. The rings cast deep shadows across blue-tinged cloud tops. NASA/JPL/SSI

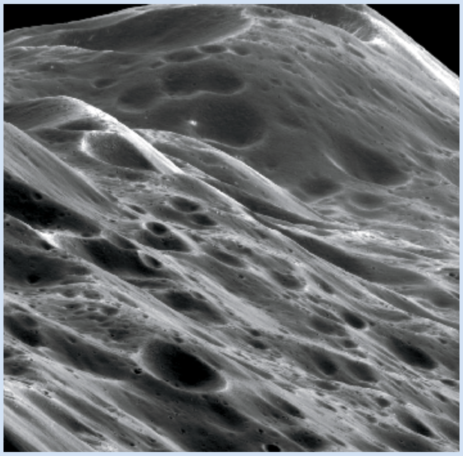


▲ A BROAD, DARK ZONE between the A and B rings of Saturn, largely devoid of ring material, marks the Huygens Gap. NASA/JPL/SSI

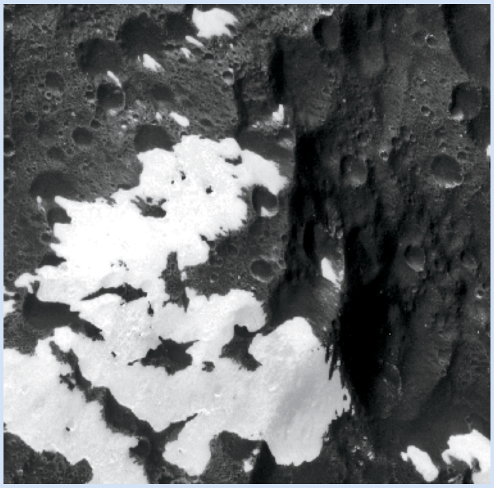




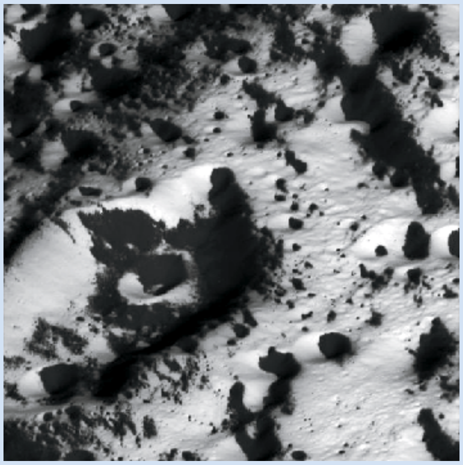
THE CASSINI ORBITER captured the first glimpse of the bright trailing hemisphere of Iapetus, Saturn's two-toned moon. The reddish tone of Iapetus' dark side is false coloring added by imaging scientists.
NASA/JPL/SSI



◄ **MOUNTAINS ON IAPETUS' prominent equatorial ridge rise 6 miles (10 km) high. Ancient impact craters cover the moon's meteor-beaten terrain.** NASA/JPL/SSI



▲ **ON IAPETUS' EQUATOR, the Voyager Mountains soar above the moon's black-and-white surface. Astronomers named these mountains after the spacecraft that discovered them.** NASA/JPL/SSI



◄ **LIGHT-COLORED WATER ICE forms Iapetus' foundation. Like raindrops collecting on the windshield of a moving car, dark material coats the moon's leading edge as it orbits Saturn.** NASA/JPL/SSI

STATISTICS: Saturn vs. Earth

	Saturn	Earth comparison
Mass	1,253 trillion trillion pounds	95 times Earth's mass
Diameter	74,898 miles	95 times wider
Density	0.69 grams/cc	12.5% of Earth's
Weight of 150-lb person	160 pounds	107% of Earth's weight
Distance from Sun	890.8 million miles	9.6 times farther
Orbital period	29.457 years	29 times longer
Length of day	10.66 hours	44.4%

Mass: Total mass (1 trillion = 10^{12}); **Diameter:** Equatorial diameter; **Density:** Average density in grams per cubic centimeter (water = 1); **Distance from Sun:** Average distance; **Orbital period:** Sidereal period; **Length of day:** Average time between successive noons; **Earth comparison:** Ratio of Saturn's to Earth's value.

The regular satellites orbit mostly in Saturn's equatorial plane. They fall into three classes: small (up to 250 miles in diameter); midsize (roughly 250 to 1,000 miles across); and one big bruiser, Titan, at 3,200 miles across.

The small and midsize satellites consist of mostly water ice, with various amounts of rock in their interiors. Impact craters dominate their surface geography, a testament to a long history of cometary bombardment.

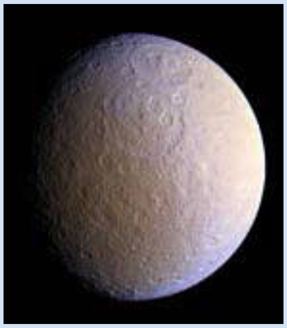
The midsize satellites show variable degrees of tectonic activity, or surface deformation. Most of the tectonic activity is extensional, meaning processes that create cracks, fissures, and downfaulting. A select few have relatively smooth areas, implying some form of "resurfacing" in the geologic past. One possible mechanism is intense faulting; another is eruptions of slushy (icy) material from below, a process called cryovolcanism.

Enceladus: the geyser moon

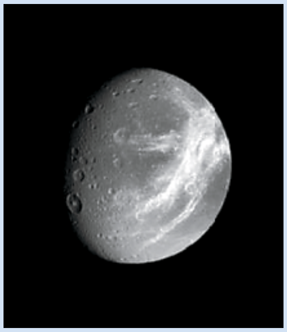
One midsize satellite stands out, diminutive Enceladus, which is 310 miles (500 km) across. It's caught in a gravitational resonance with a larger outer moon, Dione, which pulls Enceladus' orbit out of round. The resulting eccentric orbit subjects the moon to Saturn's waxing and waning gravitational tug. The result is constant flexing of the moon's interior.

The flexing generates heat, much like bending a metal wire back and forth. Enough heat is present that Cassini can measure it. The heat is also sufficient to drive active, ongoing, and observable cryovolcanism.

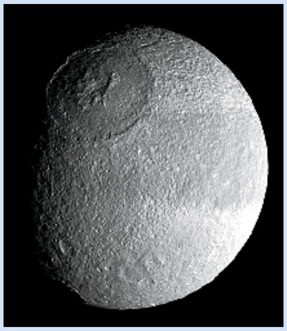
Enceladus' surface has been nearly completely remade. While some moderately cratered regions remain, most of its surface is highly deformed and nearly crater free. Four prominent fissures at the south pole, dubbed



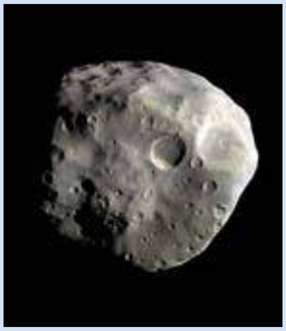
TWO LARGE IMPACT craters mar Rhea's surface, otherwise coated uniformly with smaller craters. NASA/JPL/SSI



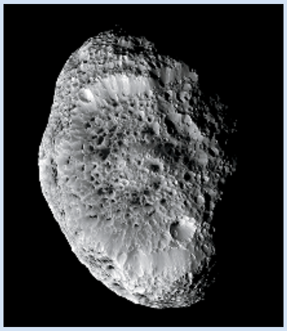
MASSIVE, BRIGHT FRACTURES slice across Dione's trailing hemisphere in this portrait Cassini captured in visible light. NASA/JPL/SSI



THE GIANT IMPACT BASIN Odysseus is the moon Tethys' claim to fame. The basin contains mountainous rings formed during the rebound from a great meteor impact. NASA/JPL/SSI



CASSINI'S COLOR PORTRAIT of the south polar region of Epimetheus reveals yellow-tinted, fractured terrain (upper right corner) contrasting with darker, heavily cratered terrain. NASA/JPL/SSI



HYPERION'S APPEARANCE may stem from the moon's large size and relatively low density. The combination imparts a spongy consistency to the moon's surface. NASA/JPL/SSI

"tiger stripes," are the sites of the excess infrared emission and active venting of water vapor and ice particles.

The vapor and particles feed the E ring, which circles Saturn centered on Enceladus' orbit. Cassini has flown right through the moon's eruption plume — twice to date — and measured carbon monoxide, carbon dioxide, water vapor, and organic molecules such as methane. So much activity in such a small package presents a delightful challenge to planetary theorists. The best thinking at present is that Enceladus harbors a watery ocean below its icy surface crust.

Iapetus: two-toned world

At the edge of the regular satellite system sails an enigma of a different order, Iapetus. Discovered in 1671 by Giovanni Cassini, Iapetus could no longer be observed when it reached its easternmost orbital position.

Cassini proposed that Iapetus had a dark and a bright hemisphere, and that it turned on its axis once an orbit — just as our Moon does. And Cassini was right. Iapetus always shows the same face to Saturn, but observers on Earth would see either its shiny (visible) side or dark (less visible) side, depending on the moon's orbital position.

Iapetus turns out to be a geologically ancient world, perhaps the oldest in the Saturn system. Impact craters, many hundreds of kilometers across, cover the moon. Its bulging equatorial zone may be the frozen vestige of an earlier, faster spin. And to top it off, a mysterious ridge encircles Iapetus, precisely on its equator. One hypothesis is that the ridge is infall from an ancient ring or moon that once circled Iapetus.

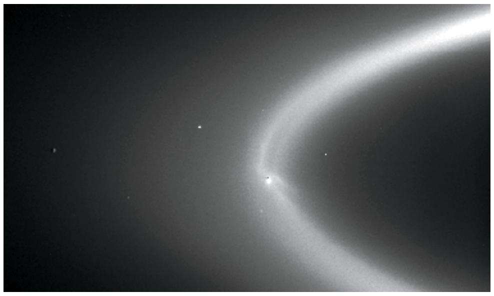
Iapetus' dark side reflects no more than 4 percent of the sunlight that strikes it. The dark zone, Cassini Regio, is centered on the apex of Iapetus' leading hemisphere of orbital motion. The darkness wraps around to the trailing hemisphere, but most of the trailing hemisphere, and the iapetan poles, are icy and bright.

The leading explanation is that dark particles from impacts on some of the irregular moons rain on Iapetus' leading hemisphere, while ice frost redistributes itself due to sublimation and condensation. But we don't know for sure if this is correct. At Saturn, some puzzles persist.

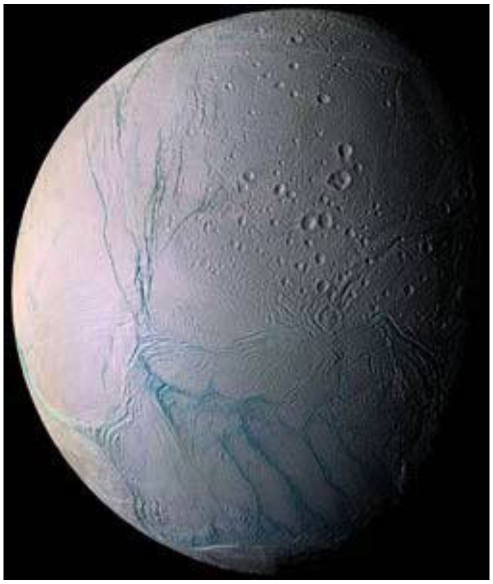
Titan: a smoggy new Earth?

And then there is Titan. This saturnian moon is larger than Mercury and is the solar system's only satellite with a substantial atmosphere.

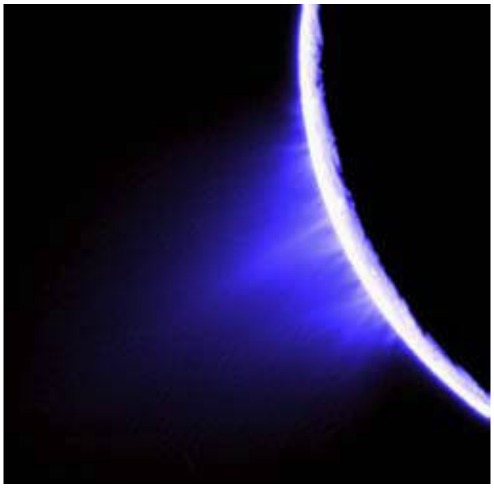
Titan hides behind a veil of smog. Although mostly nitrogen, the moon's atmosphere also contains a lot of methane. It is the reaction of this methane with UV radiation from the Sun that generates Titan's obscuring pall.



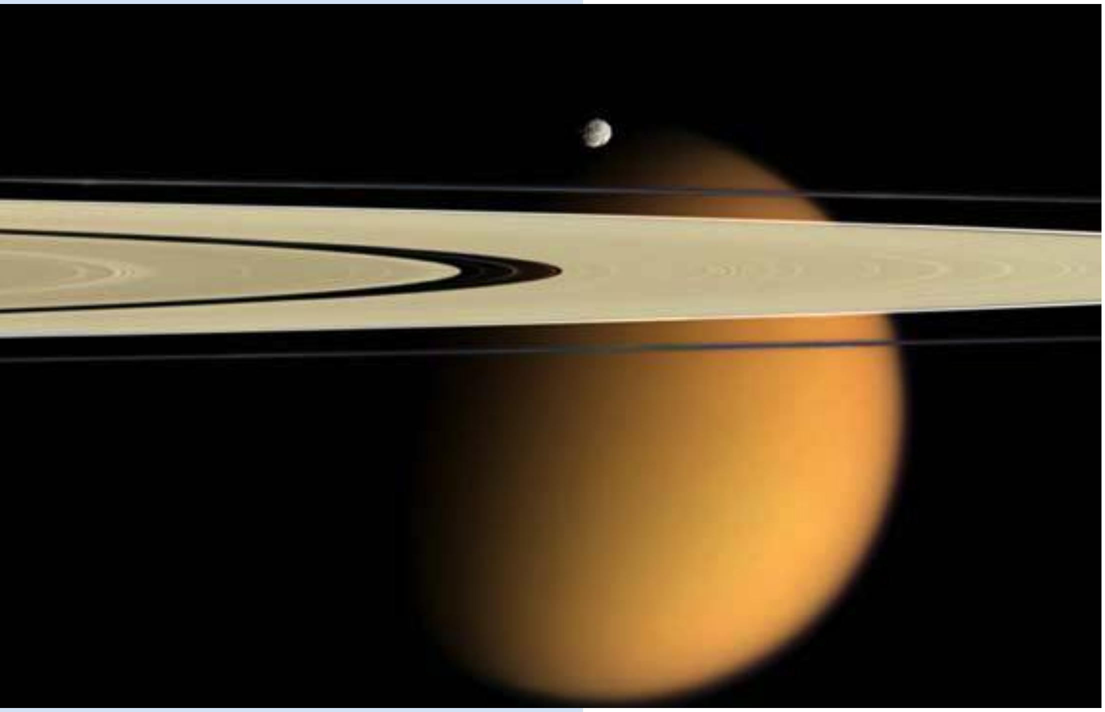
▲ **MICROSCOPIC ICE PARTICLES** spewing from the surface of Enceladus fill Saturn's E ring. The moon is visible as the bright white spot amid the fog of ring particles. NASA/JPL/SSI

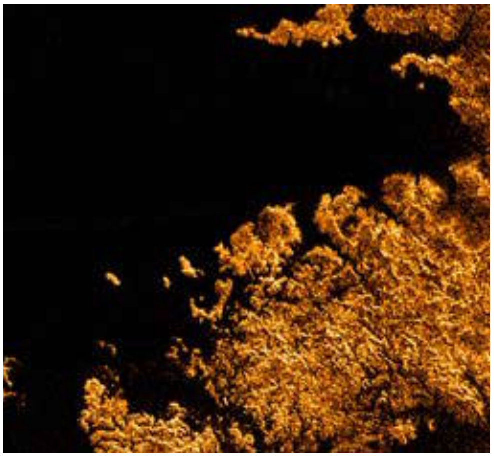


► **THE CELEBRATED "TIGER STRIPES"** of Enceladus adorn this color-enhanced Cassini portrait. The stripes mark fractures in the moon's icy crust where plumes of warm material erupt to elevations of 100 miles (160 km) or more. NASA/JPL/SSI



▲ **CASSINI IMAGING SCIENTISTS** enhanced this color snapshot of Enceladus' edge to highlight individual jets spewing ice particles, water vapor, and organic compounds into space. The scientists identified eight individual jets feeding a larger plume. NASA/JPL/SSI





▲ **TITAN'S INLAND SEAS** have complex coastlines indistinguishable from those on Earth. This coast may be part of a flooded mountain range. NASA/JPL

◄ **SATURN'S LARGEST MOON,** Titan, looms in the background while tiny Epimetheus floats above the ring plane. At 3,200 miles (5,150 km) wide, Titan dwarfs 72-mile-wide Epimetheus. NASA/JPL/SSI

▲ **CASSINI'S RADAR** system captured abundant evidence for flowing liquids on Titan. In this image, branching drainage channels form rugged terrain in Titan's south polar region. NASA/JPL/SSI

INSIDE TITAN

TITAN'S INTERIOR STRUCTURE remains a mystery. But planetary scientist Giuseppe Mitri of NASA's Jet Propulsion Laboratory has developed a theoretical model of Titan's interior that describes one possibility. In Mitri's model, Titan has a warm rocky core surrounded by a layer of compressed ice about 1.4 times denser than common ice. (The compressed layer formed as Titan was cooling and contracting in the early solar system.) An ocean of water and ammonia underlies Titan's frozen outer crust.

ASTRONOMY: JAY SMITH

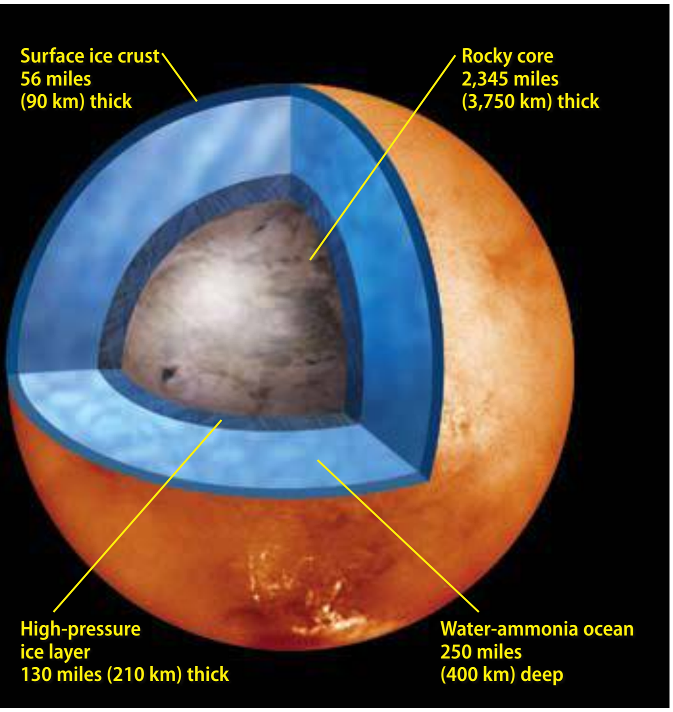


Illustration not to scale

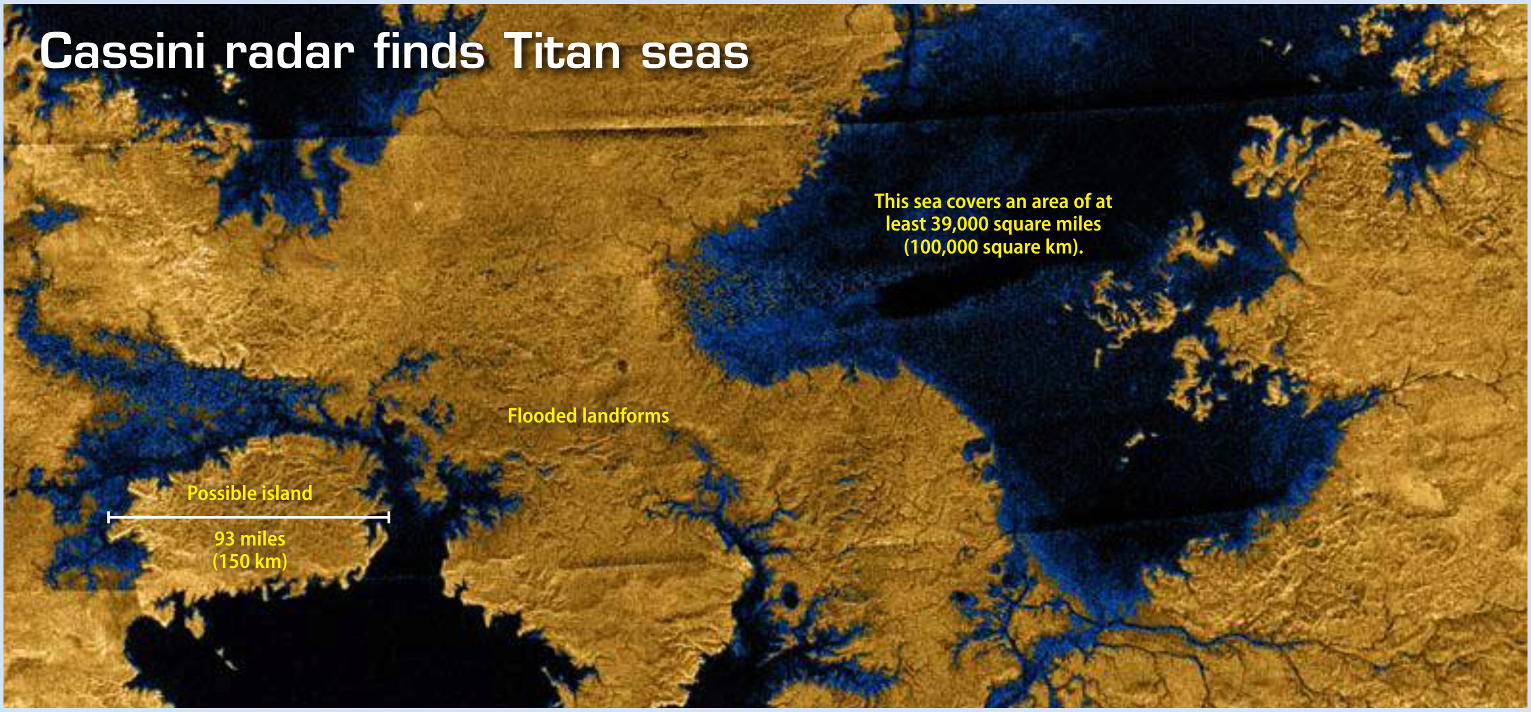
Fortunately, it is possible to see through Titan's atmosphere at certain near-infrared wavelengths and by using radar. Cassini's imaging and radar systems can do both. The landscape revealed is astonishingly earthlike, with deeply eroded terrains, winding river valleys, integrated drainage systems, outwash plains, and probably hydrocarbon lakes.

All this takes place, amazingly enough, at surface temperatures of only –291° Fahrenheit (–180° Celsius). Titan's crust appears to be primarily water ice, but the fluid responsible for the channels and the lakes is liquid methane as well as liquid ethane, another product of the photochemistry in Titan's atmosphere.

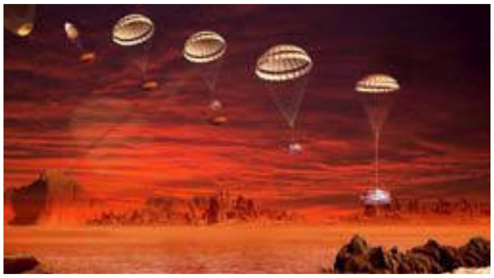
Scientists had long anticipated that Titan would possess surface liquids, based on its estimated surface temperature and the atmosphere's composition. Imagine everyone's surprise when the dark, low-lying expanses of Titan — originally discovered from ground-based and Hubble Space Telescope observations — turned out not to be liquid at all, but seas of dark sand.

The sand may also be rich in organic material and carbon, and therefore a product ulti-

Cassini radar finds Titan seas


This sea covers an area of at least 39,000 square miles (100,000 square km).
Flooded landforms
Possible island
93 miles (150 km)

▲ **CASSINI'S IMAGING RADAR scanned Titan's surface February 22, 2007, to create this false-colored image of what are probably methane-ethane lakes. Bright, jutting shorelines suggest eroded and flooded landforms. An island as large as Hawaii's Big Island appears in one lake. Cassini did not completely capture the largest lake, at the far right. But what the orbiter did see covers a greater area of Titan's surface than the Black Sea does on Earth.** NASA/JPL/USGS



▲ **THE EUROPEAN SPACE AGENCY'S Huygens probe descends by parachute to Titan's surface in this artist's concept. The NASA Cassini orbiter released the probe December 24, 2004.** NASA/JPL/ESA

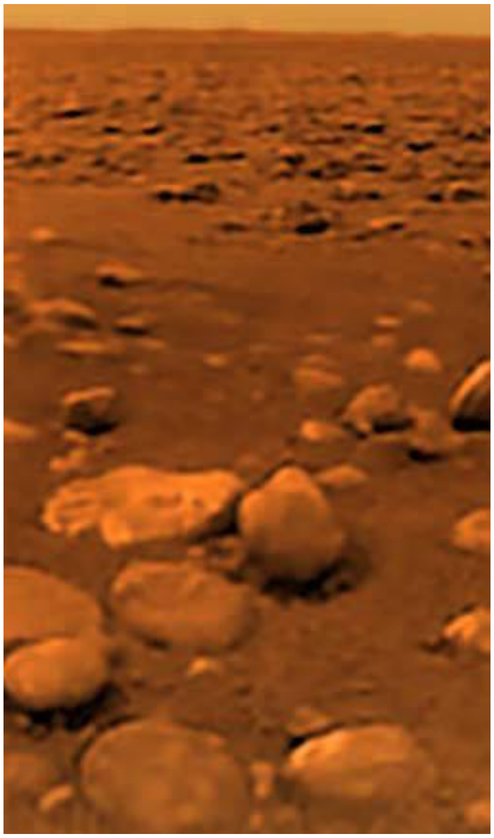
◄ **IN THIS CRESCENT PORTRAIT, Titan's orange globe shines softly, fringed by a thin halo of purple light-scattering haze. Titan is the only moon in the solar system with a substantial atmosphere.** NASA/JPL/SSI

mately of atmospheric chemistry. The liquids eventually showed up at Titan's poles, where it is just a bit colder than average, but apparently cold enough for ethane-methane rain to fall.

The Huygens lander set down in an apparent outwash plain or flat, resting on some sort of ice sand or gravel moist with liquid methane. The rounded ice cobbles in the foreground of the lander's view indicate water erosion. Huygens landed in Titan's "tropics," and thus nowhere near the lakes. But as the first landing on a moon of the outer solar system, Huygens' feat was a harbinger of things to come.

We have traveled a long way since 1610, but on Saturn enigmas sometimes last for centuries. The many mysteries of active moons, rings, and atmospheres beckon.

Return missions to Titan may feature a mobile balloon or aircraft to sample the moon's landscape more widely. Such a mission is technically feasible and planetary scientists eagerly await its coming. The ongoing, complex organic chemistry in Titan's atmosphere and on its surface is what most intrigues scientists. It offers a window into nature's kitchen, and the still-secret recipe for life. ◘



▲ **THE FIRST SURFACE VIEW from the Huygens lander revealed highly eroded stones and pebbles. Signs of erosion at the stones' bases suggest the site may have experienced flowing liquid methane in the past.** ESA/NASA/JPL/UNIVERSITY OF ARIZONA

Inside the solar system's icy giants

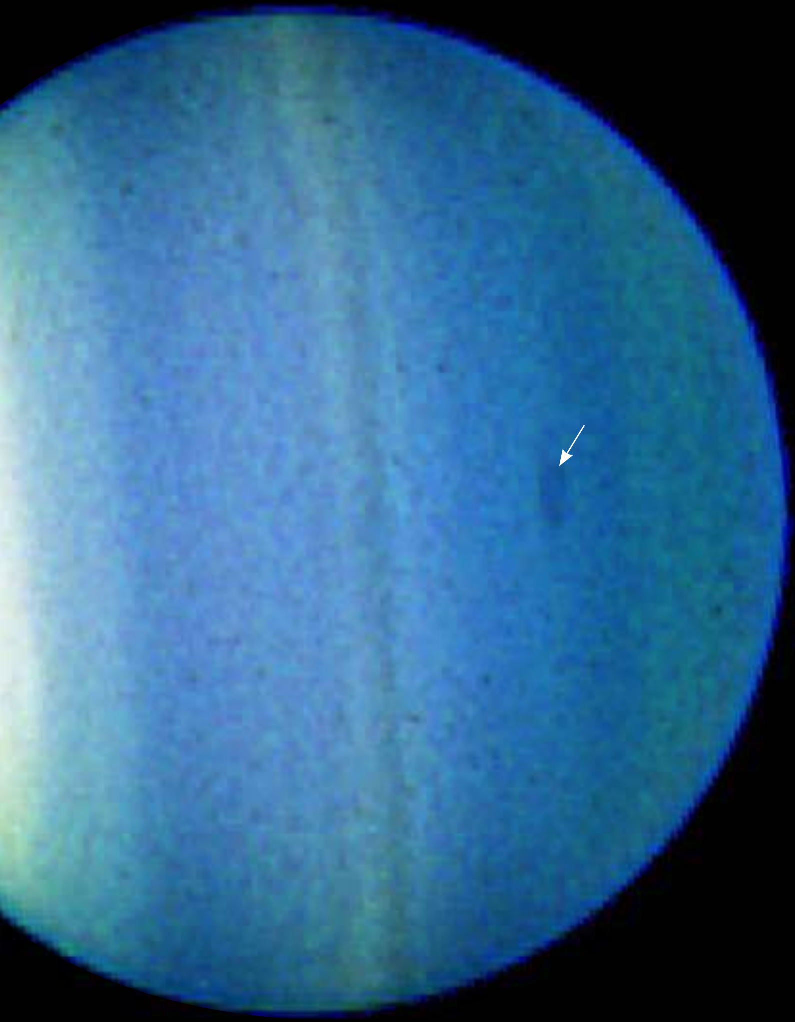
New observations of atmospheres, rings, and moons give planetary scientists insights into Uranus and Neptune. **by Heidi B. Hammel**

Our solar system's outermost two major planets — Uranus and Neptune — have gained in importance as astronomical technology and observational techniques have advanced. Perhaps most intriguing of all, astronomers have discovered that these planetary systems are in the midst of changing.

Uranus and Neptune differ from Jupiter and Saturn in more than just size and color: Uranus' and Neptune's interiors differ in composition and structure; their zonal winds differ in magnitude and direction; and their magnetic fields differ in structure. Astronomers classify these intermediate-sized planets as "ice giants" to distinguish them from their larger gas-giant cousins. (By "ice," scientists mean their relatively large internal abundances of materials such as methane and water as compared with the nearly all-hydrogen gas giants). The increasing number of Neptune- and Uranus-sized bodies discovered around other stars is causing astronomers to take a closer look at our two outer planets.

The uranian system

Uranus is best known for its extreme obliquity, or axial tilt, of 98°. It appears to spin on its side. Early in its history, the planet probably experienced a catastrophic collision: an impact so severe Uranus twisted completely over, where it spins to this day. Yet in spite of that exciting past, Uranus has been typecast as the solar system's most boring planet.



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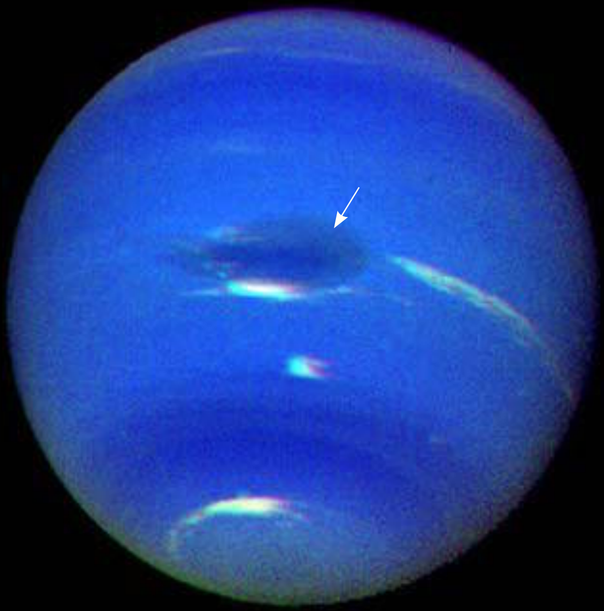

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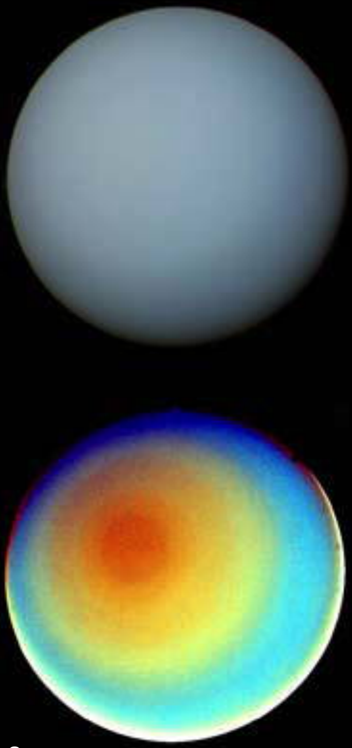
► **URANUS AND NEPTUNE reside in the solar system's farthest reaches. Earthbound and space telescopes reveal the intriguing features of these cold gaseous worlds. 1) The first dark spot seen on Uranus (arrow) lies to the right of center in this Hubble Space Telescope image taken August 23, 2006. 2) Neptune's Great Dark Spot (arrow) was prominent when Voyager 2 flew 3,000 miles (4,800 km) above Neptune August 25, 1989. 3) Astronomers used Voyager 2 to take images of Uranus in true (top) and false colors in January 1986 to discover how its atmosphere absorbs the reddish component of sunlight. This gives the planet an overall blue-green appearance. 4) Uranus showed four rings and bright clouds in this Hubble infrared image taken August 8, 1998.** PHOTOMONTAGE: *ASTRONOMY*: KELLY KATLAPS; IMAGES: NASA



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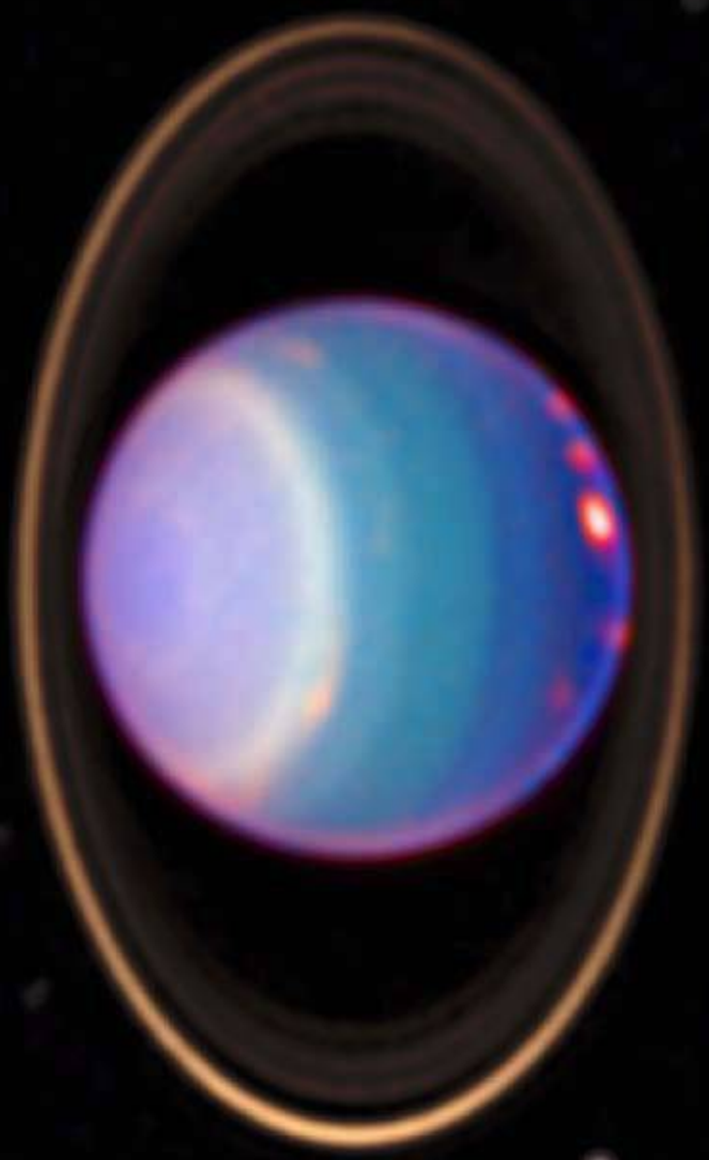

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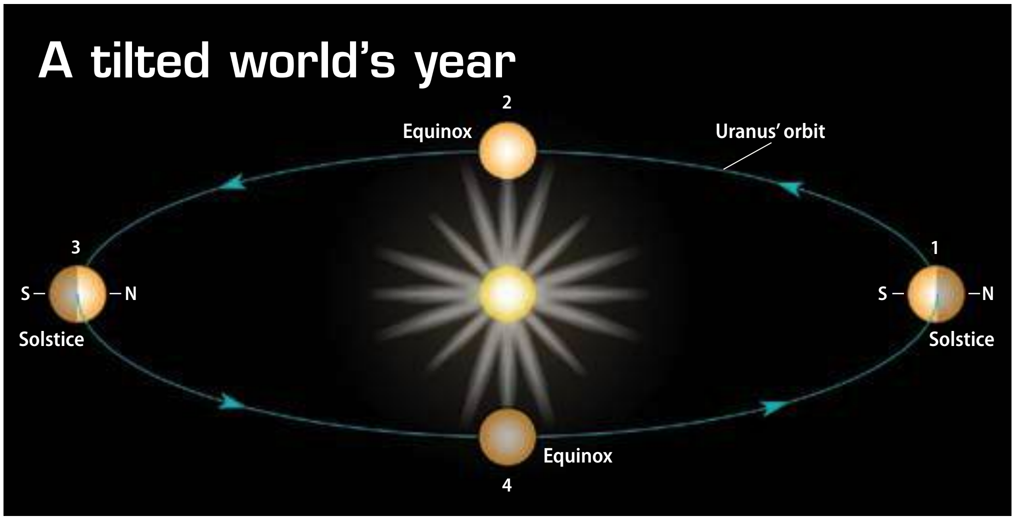


▲ URANUS ORBITS THE SUN in about 84 years. The southern-hemisphere solstice (1) occurred in 1985; Voyager 2 flew by the following year. The equinox, or ring-plane crossing (2), happened in late 2007 and early 2008. The next solstice (3) will occur in 2028, when the Sun fully illuminates the planet's northern hemisphere. Uranus won't reach its next equinox until 2049 (4). HEIDI B. HAMMEL

STATISTICS: Uranus vs. Earth

	Uranus	Earth comparison
Mass	191.4 trillion trillion pounds	14.54 times Earth's
Diameter	31,763 miles	400 times Earth's
Density	1.27 grams/cc	23.0% of Earth's
Weight of 150-lb person	136 pounds	90.5% of Earth's
Distance from Sun	1,785 million miles	19.2 times Earth's
Orbital period	84.01 years	84 times Earth's
Length of day	17.24 hours	71.8% of Earth's

Mass: Total mass (1 trillion = 10^{12}); **Diameter:** Equatorial diameter; **Density:** Average density in grams per cubic centimeter (water = 1); **Distance from Sun:** Average distance; **Orbital period:** Sidereal period; **Length of day:** Average time between successive noons; **Earth comparison:** Ratio of Uranus' to Earth's value.

When Voyager 2 flew over the uranian cloud tops in 1986, its cameras discerned almost no contrast, tallying up just 10 or so discrete clouds, compared with Saturn's hundreds and Jupiter's thousands. But Uranus' atmospheric dormancy may have been a fluke. It was the height of the uranian southern summer, and the planet's pole had been baking in the Sun's glow for decades. Such conditions do not promote the formation of clouds.

In December 2007, the Sun fully illuminated Uranus for the first time in 42 years. The formerly bland atmosphere appears to be responding rapidly to illumination changes.

Uranus' atmosphere

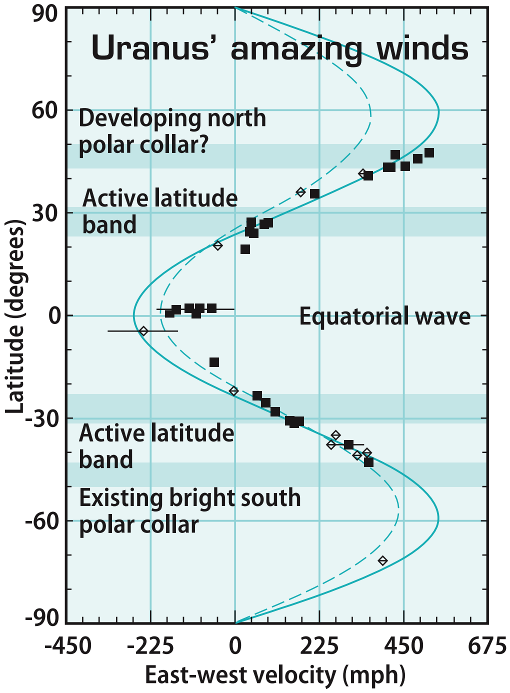
Any planet with an axial tilt experiences seasons. On Uranus, however, seasonal change is radical. The poles spend decades either basking in unrelenting sunshine or radiating heat into space. Even so, early models predicted a negligible seasonal effect, at least in visible regions. The blank atmosphere the Voyager cameras imaged seemed to vindicate this, revealing a docile world.

Hubble Space Telescope observations of Uranus provided the first hint of the atmosphere's seasonal change. Hubble visible-wavelength images taken by Kathy Rages of the SETI Institute in Mountain View, California, and her colleagues revealed the polar region darkened as it received less direct sunlight.

Images taken with Hubble's infrared camera by Erich Karkoschka of the Lunar and Planetary Laboratory at the University of Arizona showed bright northern hemisphere clouds. One cloud had the highest contrast ever recorded for an outer planet, a dramatic change from the low-contrast features Voyager imaged. Images from Hubble and from Keck Observatory in Hawaii showed tremendous cloud activity across the planet. They included air movement on short time-scales and the first detection of a planet-wide wave feature in Uranus' equatorial clouds.

Using Voyager images, scientists tracked its few southern hemisphere clouds. This allowed measurement of the planet's zonal, or east-west, wind speeds. A single equatorial wind speed determined by a Voyager radio science experiment supplemented those data. With Keck and Hubble images of Uranus, I extracted new wind measurements — not only in the south to confirm Voyager results, but also for the first time of northern winds.

Uranus' winds, like Neptune's, show a retrograde equatorial flow, along with strong mid-latitude prograde jets in both hemispheres.



▲ EAST-WEST WINDS approach 500 mph (800 km/h) on Uranus. We measured the solid squares in 2003 with the Keck Telescope; open symbols are past data from Hubble, Keck, and Voyager 2. HEIDI B. HAMMEL ET AL.

Some evidence suggests Uranus' zonal winds vary with time. How we view features also may be the cause. At the limb, we see them at higher altitudes. When such features lie farther on the disk, we observe their deeper components.

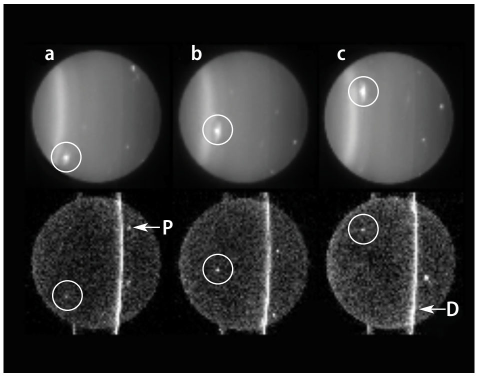
Uranus' atmosphere appears strikingly asymmetric at most near-infrared wavelengths. Scientists do not understand why the planet's appearance is changing, nor what links its upper and lower atmospheric layers. We expect more clues to emerge as the planet moves through its equinox (when the Sun lies directly above its equator) and beyond.

Colorful rings

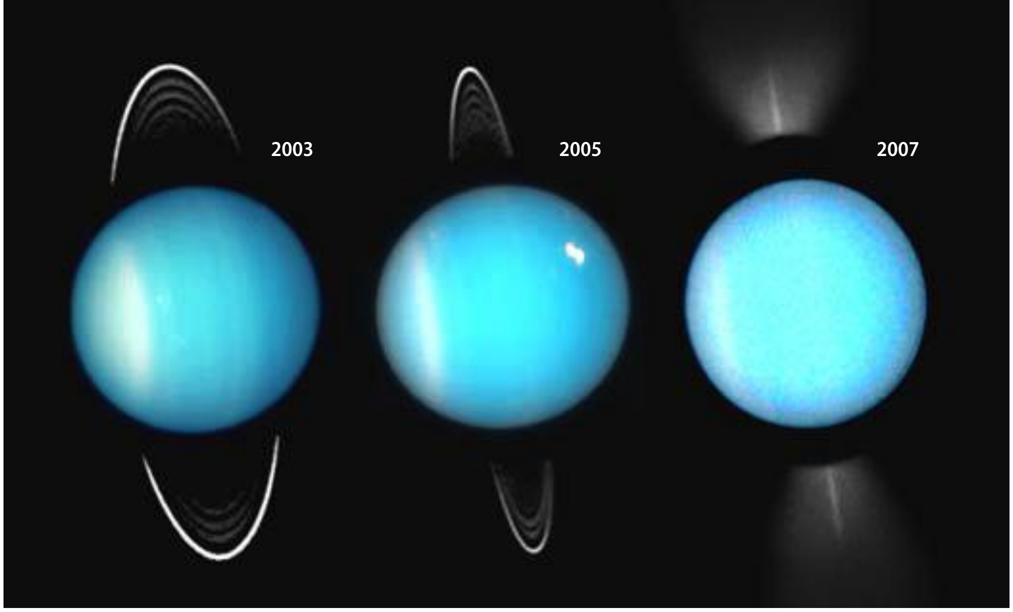
In recent years, Imke de Pater of the University of California at Berkeley, Mark Showalter of the SETI Institute, and my colleagues have studied the uranian ring system with the Keck and Hubble telescopes. By modeling the rings' brightnesses, the scientists also detected narrow (a few hundred kilometers wide) dust sheets between Uranus' Delta (δ) and Epsilon (ε) rings, and between rings 4 and Alpha (α).

The distribution and relative intensities of these dust sheets differ from what Voyager 2 imaged. This may be due to the different observing wavelengths and the Sun angle, to changes over time, or a combination of both.

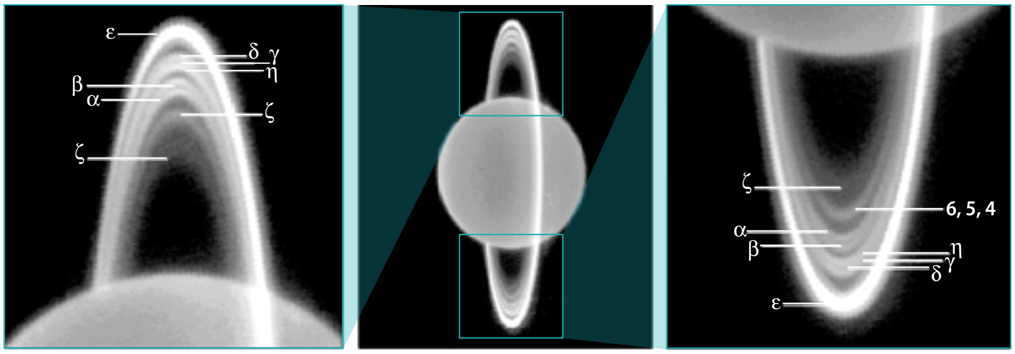
Heidi B. Hammel *is a senior research scientist with the Space Science Institute in Boulder, Colorado.*



THE KECK 10-METER TELESCOPE took these images of Uranus in July 2004. Uranus' south pole is to the left. Astronomers acquired the upper images through a 1.6 µm microwave band filter. The lower row shows the planet photographed through a 2.2 µm microwave band filter. At 2.2 µm, the planet appears dark because methane absorbs light. Rings and satellites that masquerade as northern cloud features dominate these images. For example, we see interloper moons Portia (labeled P) and Desdemona (D). These images contain rare and unusual features (circled), including the first and only southern hemisphere feature detected at the 2.2 µm wavelength. HEIDI B. HAMMEL ET AL.



THIS SERIES OF HUBBLE images shows how Uranus' ring system appears at increasingly shallower angles. Earthbound observers see the rings edge-on only every 42 years. NASA/ESA/M. SHOWALTER (SETI INSTITUTE)



ASTRONOMERS PHOTOGRAPHED URANUS' MAIN RING SYSTEM in 2004. Most of the ring components (the ε ring; the α and β pair; the trio η, γ, and δ; the cluster containing 6, 5, and 4; and the newly named ζ ring) appear in this Keck 10-meter telescope image. IMKE DE PATER ET AL.

How many uranian moons?

Prior to 2003, astronomers had found 25 moons near Uranus, although one of these, Perdita, was unconfirmed. The near edge-on equinox view of the uranian system was optimal for finding moons. Satellites appear to move more slowly when they are at the "tips" of their orbits as viewed from the side, and hence are easier to detect. Mark Showalter and Jack Lissauer of NASA's Ames Research Center used Hubble in 2003 to confirm Perdita's existence and to discover two new moons, Mab and Cupid. Their discoveries brought the system's total to 27.

As equinox nears for Uranus, the moons' northern hemispheres tilt sunward, yielding some surprises. Recent near-infrared spectra of Ariel by Will Grundy of Lowell Observatory in Flagstaff, Arizona, and his colleagues revealed the signature of frozen carbon-dioxide (CO_2), what we call "dry ice." Not only is this the first CO_2 ice detected in the uranian system, but it is also the first new species of ice discovered on a uranian satellite in 20 years.

The CO_2 ice raises some questions: Why is it only on Ariel? How much is there? How is it distributed? Where did it come from? How long will it survive? Future observations may resolve these mysteries.

URANUS HAS BEEN TYPECAST AS THE SOLAR SYSTEM'S DULLEST PLANET.

The tritium up there

Current research on the upper part of Uranus' atmosphere, its electrically charged ionosphere, focuses mainly on detecting near-infrared emission from excited tritium ($H3^+$) ions.

Oddly, Uranus' emission appears to be stronger than Saturn's, according to Thomas Geballe of Gemini Observatory in Hilo, Hawaii, and his colleagues. This is puzzling because Saturn undergoes lots of auroral activity. Tritium emission intensity would likely decrease farther from the Sun. The solution to this puzzle requires more accurate information about the characteristics and behavior of the $H3^+$ emissions on both Saturn and Uranus.

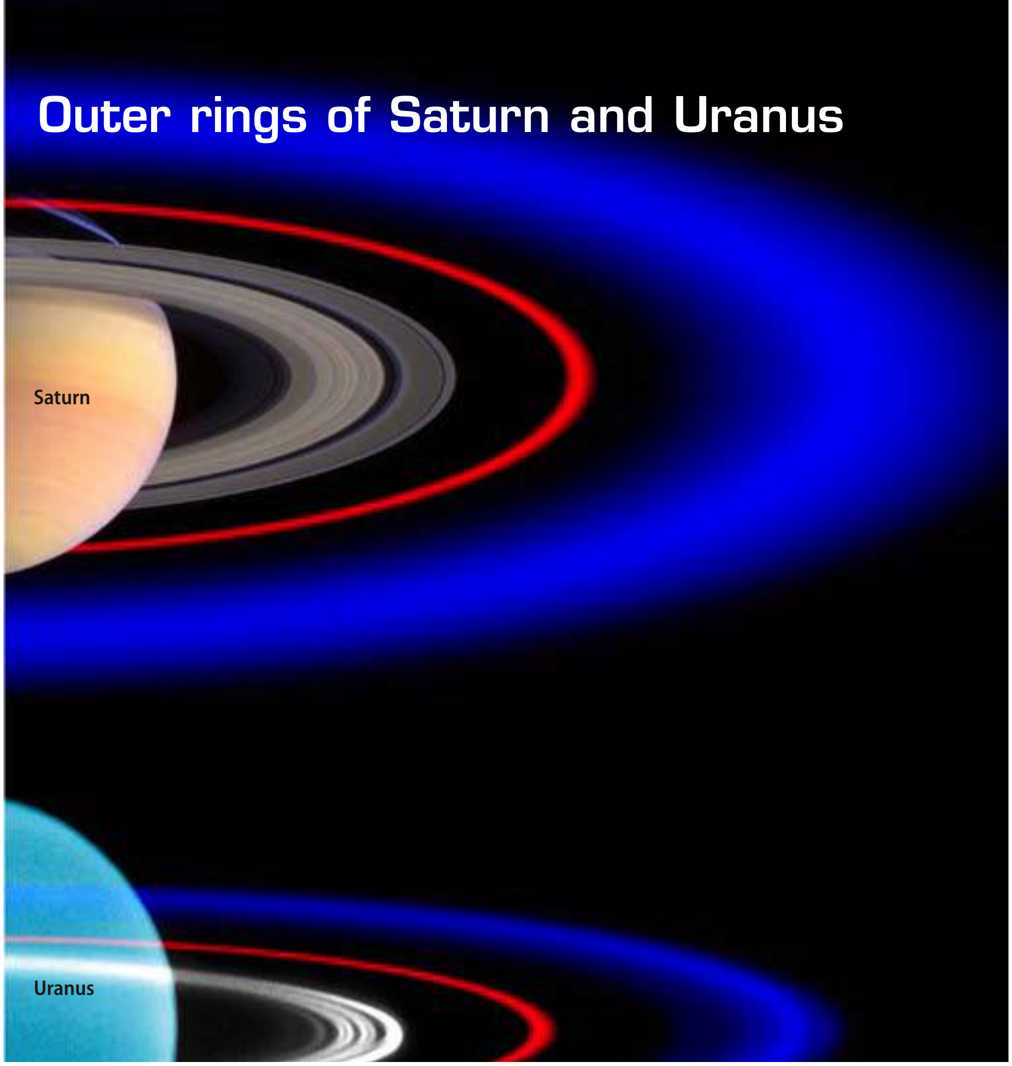
Fortunately, Uranus' equinox provides investigators with the first opportunity to examine daily variations of the ionosphere. For typical conditions, the chemical lifetime of $H3^+$ is less than 3 hours, much less than Uranus' rotational period of about 17 hours. This means $H3^+$ concentrations on the night side should be low, with emission ramping up from the sunrise limb to a broad maximum in the late afternoon approaching the evening limb.

In 1999, Larry Trafton of the University of Texas at Austin and Steve Miller of University College London saw hints of this predicted behavior. Additional observations at equinox — when this effect is at a maximum — will yield information on Uranus' ionospheric processes.

The Neptune system

If Neptune is Uranus' twin, then it is a fraternal twin: The atmosphere, moons, and ring system all differ markedly from their uranian counterparts. Current knowledge of this distant yet dynamic ice giant highlights differences between Neptune and its planetary sibling.

Neptune varied a lot. Prior to 1989, the best pictures of Neptune from Earth's surface showed discrete bright clouds and a bright south polar region. In 1989, the Voyager 2 spacecraft confirmed these aspects and revealed a surprisingly large, dark storm system in the


Outer rings of Saturn and Uranus
Saturn
Uranus

▲ **USING KECK AND HUBBLE'S combined power, Imke de Pater and colleagues found Uranus' two new outer rings resemble Saturn's outer rings. Here, the relative colors of Uranus and Saturn outer rings are correct. Many scientists ascribe Saturn's blue E ring to the dust, gas, and ice particles spewed into Enceladus' orbit by plumes on its. This is unlikely to be the case, however, with the tiny moon Map, embedded in Uranus' blue ring. Instead, both rings may owe their color to subtle forces acting on ring dust that allows smaller particles to survive while the embedded moons recapture larger particles.** MARK SHOWALTER/HEIDI B. HAMMEL

STATISTICS: Neptune vs. Earth

	Neptune	Earth comparison
Mass	225.8 trillion trillion pounds	17.15 times Earth's
Diameter	30,775 miles	3.9 times Earth's
Density	1.64 grams/cc	29.7% of Earth's
Weight of 150-lb person	171 pounds	114% of Earth's
Distance from Sun	2,793 million miles	30 times Earth's
Orbital period	164.8 years	165 times Earth's
Length of day	16.11 hours	67.1% of Earth's

Mass: Total mass (1 trillion = 10^{12}); **Diameter:** Equatorial diameter; **Density:** Average density in grams per cubic centimeter (water = 1); **Distance from Sun:** Average distance; **Orbital period:** Sidereal period; **Length of day:** Average time between successive noons; **Earth comparison:** Ratio of Neptune's to Earth's value.

▲ **NEPTUNE'S CIRRUS CLOUDS float high and glow brightly in the planet's atmosphere in this Voyager 2 image taken 2 hours before the spacecraft's closest approach August 25, 1989.** NASA

southern hemisphere named the Great Dark Spot, or GDS. Using Hubble in 1994, my colleagues and I discovered that the Voyager GDS had disappeared — and that a new one had formed in Neptune's northern hemisphere.

Neptune's clouds change rapidly, often forming and dissipating over several hours. The planet's banded structure changes on longer timescales. Hubble images show a steady buildup of activity at southern middle latitudes. Ground-based, near-infrared Keck images also show this activity. No suitable mechanism yet explains Neptune's dynamic atmosphere.

Longer-wavelength studies reveal long-term changes in Neptune's stratospheric temperature. Scientists see a trend of increasing temperature with time. Observations of molecular abundance at submillimeter wavelengths by Andre Marten of the Observatoire de Paris in France and colleagues show the trend, as do observations of hydrocarbon emission at mid-infrared wavelengths by my colleagues and me. We don't yet understand what drives these upper atmospheric changes.

A model by Lawrence Sromovsky of the University of Wisconsin-Madison and his colleagues suggests the seasons drive long-term change, as they do on Uranus. Older data do not support the model. I suggest a subtle response to solar variations causes long-term change on Neptune, but the debate goes on.

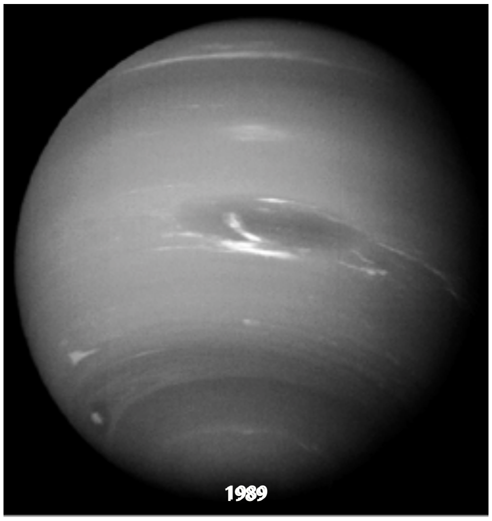
TRITON HAS AN ATMOSPHERE COMPOSED PRIMARILY OF NITROGEN.

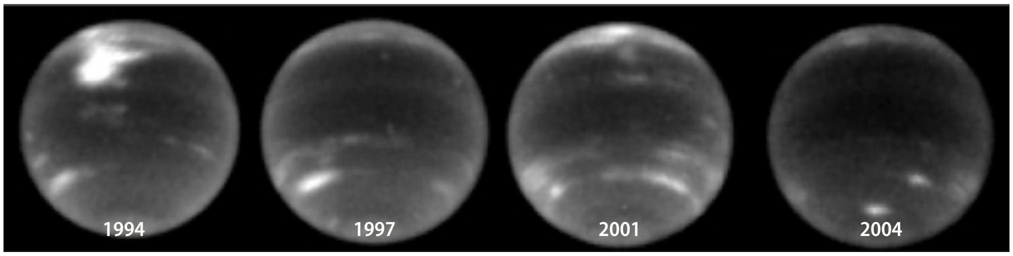
Clumpy rings

Several ground-based telescopic observations show rings around Neptune, but paradoxically, others do not. After astronomers processed Voyager 2 images, they revealed five rings: two bright, narrow rings and three fainter, fuzzier sheets. Some sections of the bright rings have significantly higher densities than others, and it was these higher-density arcs that telescopes on Earth detected occasionally.

Keck images taken in 2002 and 2003 by de Pater and colleagues revealed Neptune's Adams and Le Verrier rings for the first time since Voyager 2 imaged them. In 2005, Mark Showalter and colleagues detected the Adams and Le Verrier rings at visual wavelengths with Hubble.

Newer Earth-based observations reveal fascinating changes in the ring system that suggest both the location and intensity of some of Neptune's ring arcs change drastically. It could be that material migrates between resonance sites, regions where gravitational and tidal influences help maintain the arcs' stability. The ring arc





◄ ▲ **NEPTUNE'S ATMOSPHERE EVOLVES. The Voyager spacecraft took the far-left image in 1989 through a broadband blue filter. Hubble obtained the other images through its WFPC2 619nm methane-band filter in 1994, 1997, 2001, and 2004, respectively. The 1994 image of Neptune shows the companion to the northern Great Dark Spot. Images in subsequent years show southern mid-latitude activity increasing (a maximum occurred in 2003). The 2004 image shows that much of that mid-latitude activity has now subsided, perhaps heralding a return to a Voyager-era cloud distribution.** HEIDI B. HAMMEL/WES LOCKWOOD

Courage has jumped forward by about 8°; arcs Egalité 1 and 2 appear to have reversed in relative intensity; and arc Liberté appeared on the verge of disappearing completely in 2003. No theory yet describes the rings' observed rapid evolution.

Icy body, warming atmosphere

Triton — Neptune's largest satellite — travels in a retrograde orbit, unlike any other large satellite. Scientists' best guess right now is that Triton is a captured Kuiper Belt object.

Voyager 2 revealed remarkable diversity on Triton. Grooves and ridges slice across an icy landscape. Other features include a cantaloupe-like terrain characterized by roughly circular depressions with upraised rims.

The similarly sized and regularly spaced depressions are probably not impact craters. More likely, they are associated with local melting and collapse. Yet other regions have dark gray markings with sharply defined bright borders. The slightly pinkish and highly reflective South polar cap may consist of a slowly evaporating nitrogen ice layer.

Triton has an atmosphere composed primarily of nitrogen, with some methane and a thin haze. The haze may be condensed atmospheric gases (nitrogen ice molecules) or complex organic molecules.

Planetary astronomer James Elliot of the Massachusetts Institute of Technology and his colleagues used Hubble in 1997 to observe Triton occulting (passing in front of) a star. The team found Triton's atmosphere since 1989 had warmed significantly faster than models had predicted. In 1997, Triton was approaching its extreme southern summer (a condition arising only every few hundred years). The observed change suggests Triton's polar caps may play a dominant role in regulating seasonal atmospheric change.

Neptune's moons

Prior to Voyager's encounter with Neptune, astronomers knew of only two satellites: Triton and Nereid. In 1989, Voyager 2 discovered six new ones. Proteus is the largest of these, just slightly larger than Nereid. Proteus' dark color and proximity to Neptune hid it from Earth-based searchers. Larissa is an irregularly shaped, dark object. The noncircular shapes of Proteus and Larissa suggest they remained cold and icy throughout much of their history. Aside from their orbits, little is known about the other four satellites Voyager found: Despina, Galatea, Thalassa, and Naiad.

The census of Neptune's moons has increased in recent years. In 2004, Holman and colleagues reported the discovery of five new, irregular moons of Neptune. The five satellites orbit Neptune at great distances, two in prograde orbits, and three in retrograde orbits. None is larger than about 30 miles (50 km) in diameter. These bodies, like Triton, may be captured objects. Alternatively, they may be the remnants of collisions between existing moons and a passing comet or asteroid.

Future ice-giant exploration

The remoteness of the outer solar system presents challenges for missions to the icy bodies residing there. Even the most optimistic scenarios for standard or nuclear launch capabilities yield travel times of a decade or longer.

Because little sunlight is available for power at the solar system's far reaches, future missions will almost certainly require nuclear power sources. NASA has considered missions to Neptune, but a launch is unlikely before 2030. Uranus does not appear on any schedule.

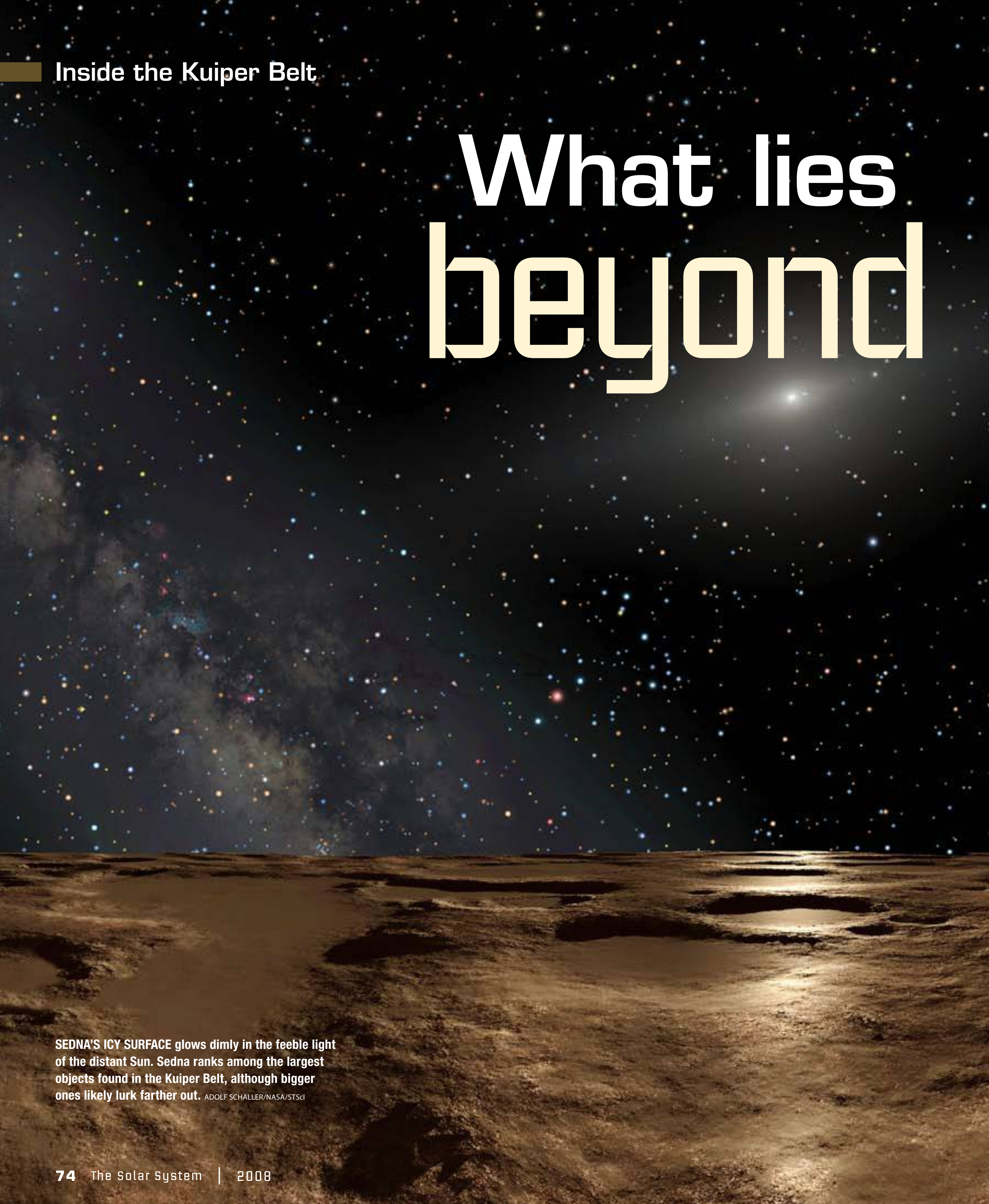
Future exploration of Uranus and Neptune will be done telescopically. Astronomers accomplished most of the work described here with ground-based telescopes and Hubble.

▲ **THIS GLOBAL COLOR MOSAIC of Neptune's largest moon, Triton, showed cracks, geysers, and dark dust particles high above the surface. Voyager 2 snapped this picture August 25, 1989.** NASA

A future facility that may yield fascinating results is the James Webb Space Telescope (JWST). Scientists plan to launch this infrared-optimized, 21.3-foot (6.5m), segmented-mirror instrument in 2013. A potential drawback is JWST's inability to track moving objects such as Neptune, Uranus, or their satellites. My JWST colleagues and I are aware of this deficiency. We hope to announce a solution soon.

In 1989, Garry E. Hunt and Patrick Moore remarked in their book, *Atlas of Uranus*, that despite Voyager's remarkably close flyby encounters with Uranus and Neptune, "The planets guard their secrets well." In the decades since this book appeared, astronomers have made remarkable progress toward understanding these ice giants. In particular, Uranus' equinox shines new light on the planet. Neptune and Uranus have many more secrets yet to be revealed, but one thing is clear: These distant denizens of deep space are fascinating and dynamic systems. ◘

What lies beyond

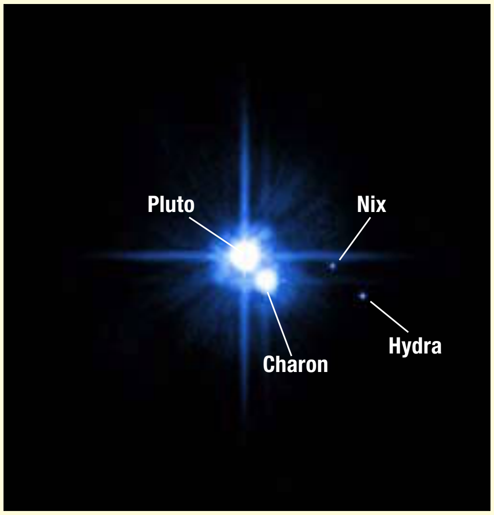


SEDNA'S ICY SURFACE glows dimly in the feeble light of the distant Sun. Sedna ranks among the largest objects found in the Kuiper Belt, although bigger ones likely lurk farther out. ADOLF SCHALLER/NASA/STScI

the planets

Everyone's heard of frigid Pluto, yet it's just the tip of the iceberg in the solar system's still-mysterious Kuiper Belt. **by S. Alan Stern**

Astronomers break down our planetary system's architecture into three distinct zones. The inner zone comprises the rocky planets and lies close to the Sun's warmth. The giant, gaseous planets dominate the middle zone. And the outer zone — called the Kuiper Belt — contains Pluto, 100,000 "ice dwarf" worlds, and several billion comets.



▲ **PLUTO'S FAMILY** now contains at least four objects: Pluto itself, the relatively large moon Charon, and the two small moons Nix and Hydra. HAL WEAVER (JHUAPL)/ALAN STERN (SwRI)/NASA/ESA

STATISTICS: Pluto vs. Earth

	Pluto	Earth comparison
Mass	0.0276 trillion trillion pounds	0.2% of Earth's
Diameter	1,485 miles	18.7% of Earth's
Density	1.75 grams/cc	31.7% of Earth's
Weight of 150-lb person	9 pounds	5.9% of Earth's
Distance from Sun	3,670 million miles	39 times Earth's distance
Orbital period	247.7 years	247.7 times Earth's
Length of day	153.3 hours	6 times Earth's

Mass: Total mass (1 trillion = 10^{12}); **Diameter:** Equatorial **diameter**; **Density:** Average density in grams per cubic centimeter (water = 1); **Distance from Sun:** Average distance; **Orbital period:** Sidereal period; **Length of day:** Average time between successive noons; **Earth comparison:** Ratio of Pluto's to Earth's value.

For centuries, astronomers have scrutinized the major bodies in the inner and middle zones. And, during the past 50 years, spacecraft have visited every planet in these zones. These probes have returned spectacular images and answered many of the mysteries surrounding these worlds.

Yet, the Kuiper Belt remains largely unexplored. No spacecraft has reached these far-flung objects. And even the most powerful telescopes on Earth and in space render these worlds as little more than faint points of light. Although this outer zone remains largely terra incognita, planetary scientists are starting to understand how the frigid outer solar system is put together.

S. Alan Stern *is the former associate administrator for the Science Mission Directorate at NASA. He is the principal investigator for the New Horizons mission to Pluto and the Kuiper Belt.*

▲ **PLUTO AND CHARON** posed for the Hubble Space Telescope's Faint Object Camera in 1994. This was the first image that clearly separated the closely orbiting, distant worlds. NASA/ESA

An undiscovered continent

Formally speaking, American astronomer Clyde Tombaugh discovered the Kuiper Belt in 1930. Using a 13-inch camera at Lowell Observatory in Arizona, he found "Planet X," an object beyond Neptune that astronomers had been trying to find for the previous quarter century.

Scientists quickly dubbed this new world both Planet 9 and Pluto, the latter after the Roman god of the underworld. Observations showed it follows an unusually elliptical and inclined orbital path. Pluto takes 248 years to orbit the Sun, coming as close to our star as 29.5 astronomical units (AU; 1 AU is the average distance between the Sun and Earth, approximately 92.8 million miles [150 million kilometers]) and heading out as far as 49.5 AU.

When Tombaugh discovered Pluto, no one fully appreciated that he had revealed a third zone of the solar system. It's not a bad analogy to liken Tombaugh's discovery of Pluto to Columbus' discovery of America. Astronomers missed the conclusion that "Planet X" is the brightest member of a vast, undiscovered population that constitutes an entirely new zone of our solar system. Similarly, Columbus thought he had found India, but instead had stumbled upon a far more significant, and then unrecognized, element of Earth's geography.

For most of the 20th century, the more scientists learned about Pluto, the more it didn't seem to fit with our solar system's eight inner worlds and myriad small bodies. Suggestions about Pluto's true context did appear, however. Dutch astronomer Gerard Kuiper (1905-1973) hypothesized that Pluto might be the first known example of a vast population of bodies, including comets and "planetoids," that reside in the cold, trans-Neptunian wilderness 30 to 50 AU from the Sun.

Then, in 1977, American astronomer Charles Kowal discovered a "miniature planet" a couple of hundred kilometers in diameter orbiting between Saturn and Neptune. Astronomers soon realized this object, 2060 Chiron, has an unstable orbit. This strongly indicates it must have come from a more distant region of the solar system. And this, in turn, suggests many more such bodies likely orbit the Sun beyond the region of the giant planets.

Later, in the 1980s, orbital simulations demonstrated that most short-period comets must originate in a disk-like reservoir beyond Neptune. This finding harkened back to the concept of a trans-Neptunian belt of primordial bodies that Kuiper had written about 4 decades earlier, spurring various searches for a trans-Neptunian "Kuiper Belt" beginning around 1988.

The clincher came in mid-1992, when David Jewitt and Jane Luu discovered a distant object orbiting on a near-circular, low-inclination orbit a billion kilometers beyond Neptune. This object, dubbed 1992 QB$_1$, was just the first of what have now become more than 1,000 similar discoveries in the space beyond Neptune.

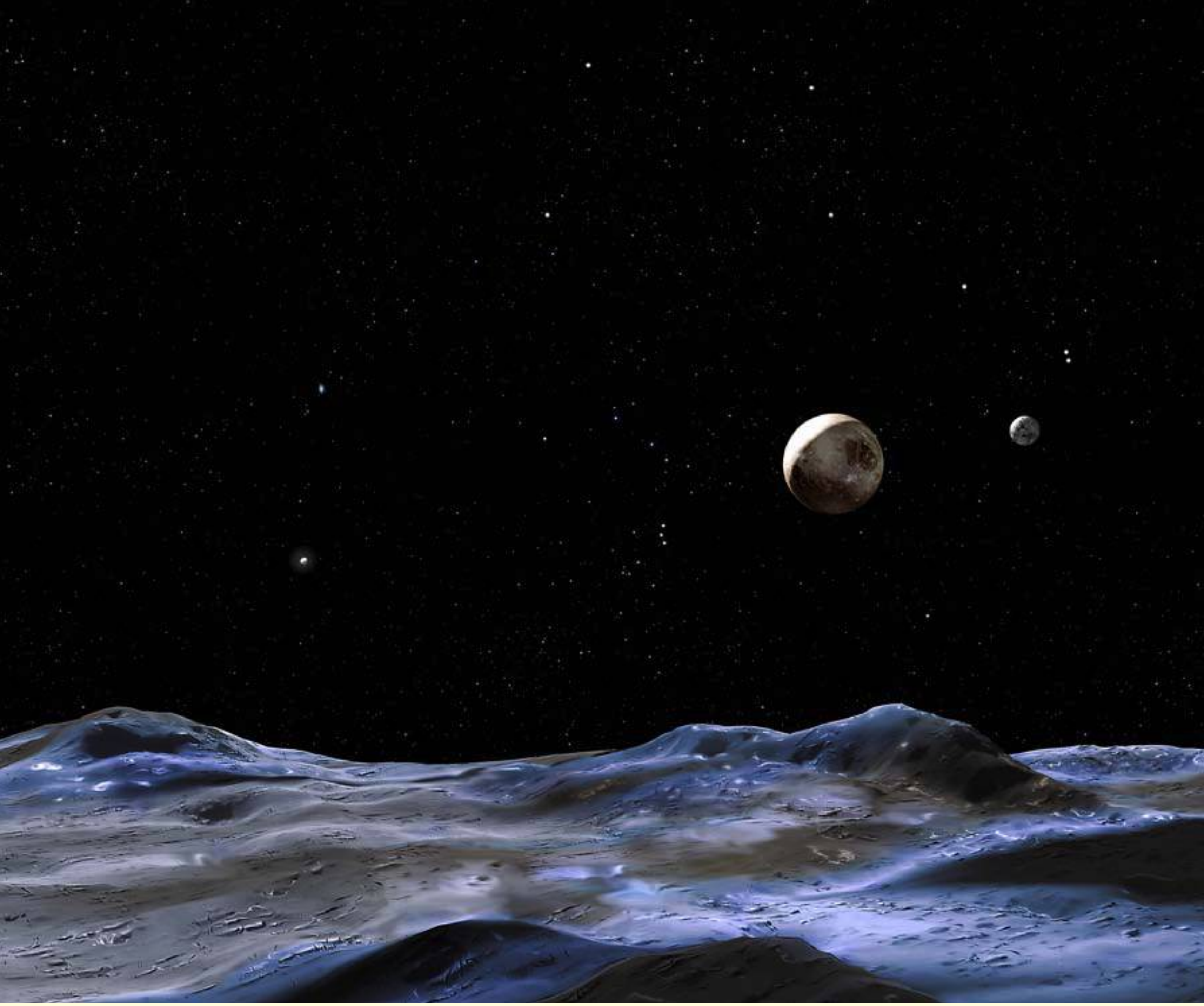
Notably, however, only about 1 percent of the sky along the ecliptic has been searched so far for Kuiper Belt objects (KBOs). When such a survey is complete, astronomers expect it will reveal more than 100,000 KBOs with diameters larger than 60 miles (100 km). Pluto's context is now clear. The Kuiper Belt occupies a far greater expanse, contains a far greater mass, and embraces a far larger and more diverse suite of bodies than does the asteroid belt.

THE KUIPER BELT REMAINS largely unexplored. ... Even the most powerful telescopes on Earth ... render these worlds as little more than faint points of light.

The Pluto system

Over the course of almost 80 years, the march of technology has allowed astronomers to learn the basics of the Pluto system — despite its great distance, faintness, and small angular diameter.

Pluto is a small planet with one large and two small moons. It measures 1,485 miles (2,390 km) in diameter. The Hubble Space Telescope barely resolves Pluto. Still, these images and other data show that it apparently has polar caps and a variety of bright and dark provinces scattered about its globe. On average, Pluto



▲ **GIANT PLUTO** **(right of center) and Charon (right of Pluto) stand watch over one of this world's recently discovered moons. The fourth moon appears as a bright dot well to Pluto's left.** NASA/ESA/G. BACON (STScI)

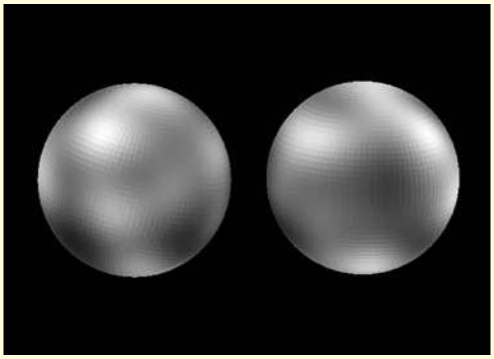
reflects 55 percent of incoming sunlight, indicating fresh ices cover the surface.

Spectroscopy shows that nitrogen ice dominates Pluto's surface composition, with small amounts of methane and carbon-monoxide ices also present. Some sort of darkening agent, with a still-undetermined composition, gives the planet a reddish color.

Pluto also has an atmosphere, which astronomers discovered by watching stars disappear behind the icy dwarf. Such occultations reveal an atmosphere when a star disappears gradually instead of abruptly. Nitrogen dominates the atmospheric composition as it does the surface.

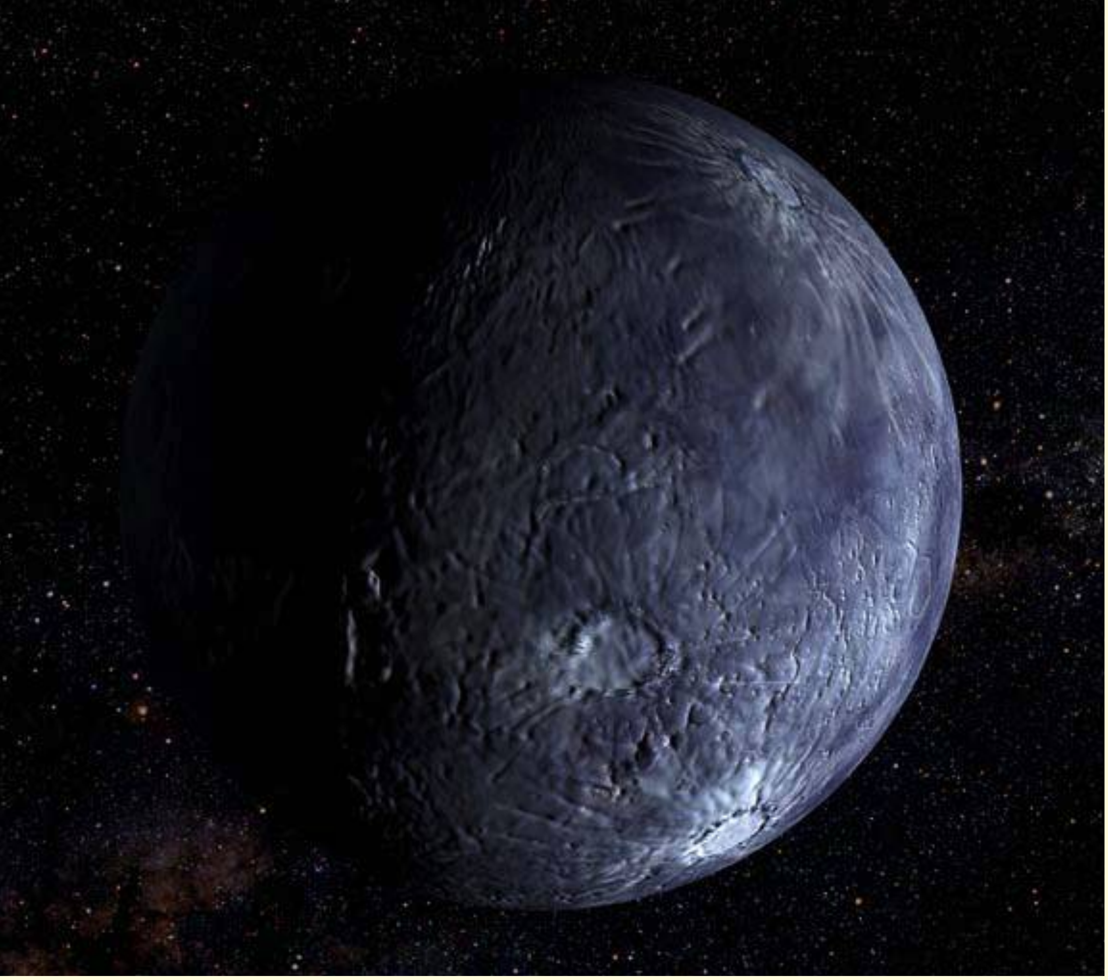
Because Pluto's gravity is so weak (just 5 or 6 percent as strong as Earth's), the planet's atmosphere escapes at a fairly high rate. Perhaps several kilometers' worth of surface ice has been lost to space over the age of the solar system. Such "escape erosion" is not found elsewhere among the known worlds of the solar system. Pluto's atmosphere also has hazes, and observers have seen its pressure change dramatically for still poorly understood reasons.

With Pluto's great distance from Earth, it should come as no surprise how long it took observers to spot the dwarf planet's moons. U.S. Naval Observatory astronomer James Christy



▲ **PLUTO'S SURFACE** **shows bright and dark areas largely covered in nitrogen-rich ices. These Hubble images, which reveal opposite hemispheres, also hint at Pluto's polar caps.**

S. ALAN STERN (SwRI)/MARC BUIE (LOWELL OBSERVATORY)/NASA/ESA



▲ KUIPER BELT OBJECT QUAOAR SPORTS A FINELY TEXTURED SURFACE in this artist's impression. Quaoar ranks among the largest of the estimated 100,000 KBOs. NASA/G. BACON (STScI)

discovered the first one, Charon, in 1978. In Roman mythology, Charon is the boatman who ferries souls of the dead across the river Styx to the underworld. The moon lies about 12,160 miles (19,570 km) from Pluto and makes a circular orbit in the planet's equatorial plane.

Charon's diameter is almost precisely half that of Pluto, a ratio no planet-satellite pair of the inner or giant planets comes close to. In fact, its size (737 miles [1,186 km] across) and mass (12 percent of Pluto's) are so large relative to Pluto that the pair makes the solar system's only true double planet — their gravitational balance point lies in the space between them rather than inside the main body.

Charon reflects less light than Pluto, returning some 35 percent of the sunlight hitting it. Unlike Pluto, water ice primarily covers Charon's surface, with trace amounts of ammonia compounds. There's no sign of nitrogen, methane, or carbon-monoxide ices.

In 2005, astronomers used the Hubble Space Telescope to search for new Pluto moons in support of the New Horizons Pluto-Kuiper Belt mission then about to be launched. They discovered two small moons. These bodies, each just 35 to 100 miles (60 to 160 km) across, orbit more than twice as far from Pluto as does Charon. Astronomers quickly named the two new moons Nix and Hydra.

In Roman mythology, Nix is the goddess of darkness and the night, and mother of Charon. Hydra is the nine-headed monster that guards the gates of the underworld. The surface colors of Charon, Nix, and Hydra are all a bland gray. Scientists do not yet have any information on the reflectivities, surface compositions, or surface appearances of Nix and Hydra.

From studies of Charon's orbit around Pluto, astronomers can determine Pluto's mass. And knowing both Pluto's mass and volume, scientists have learned that the dwarf planet's density measures close to 2 grams per cubic centimeter. This means Pluto must contain about 70-percent rock inside, in addition to its surface ices. Thus, although scientists often refer to Pluto as an icy world, it is primarily rocky.

The third zone

It has now been 16 years since the discovery of 1992 QB_1, and the subsequent realization that a vast assemblage of icy bodies rings our solar system. The objects range in size from cometary nuclei a mile or less in diameter to dwarf planets many hundreds to more than 1,550 miles (2,500 km) across. Astronomers estimate the Kuiper Belt's total mass today at between 0.01 and 0.1 Earth-mass.

▲ DWARF-PLANET ERIS, seen here with its faint moon Dysnomia (at the 8 o'clock position), currently ranks as the solar system's largest dwarf planet, besting even Pluto. NASA/ESA/M. BROWN (CALTECH)

Most Kuiper Belt objects have relatively dark surfaces, typically reflecting just 3 to 15 percent of the light that falls on them. A small fraction have higher albedos, notably Pluto and Charon. In Pluto's case, the high albedo of 55 percent arises because its atmosphere regularly deposits fresh snow on its surface. The surface colors of KBOs range widely, from slightly bluish to extremely red. Astronomers also have unearthed evidence for water ice on some KBOs, like Charon, and even more-volatile substances, like nitrogen, methane, and carbon-monoxide ices, just as on Pluto.

Most of the KBOs studied so far appear to rotate on their axes in a few hours, although some take days. In 2001, researchers found the first KBO moons. Today, astronomers recognize that at least 20 percent of KBOs have moons.

Astronomers also have found that collisions play a key role in the Kuiper Belt, shaping the surfaces of KBOs and controlling the number of small bodies there. This realization led to the discovery that those short-period comets originating in the Kuiper Belt are fragments chipped off larger KBOs only millions to hundreds of millions of years ago.

Some KBOs have small moons, some have large moons, and others, like Pluto, have both. A moon allows researchers to calculate the main body's mass, and thus estimate its density. So, we've learned that while some KBOs consist primarily of rock with icy outer shells like Pluto, others are practically all ice.

How did the Kuiper Belt and KBOs form? Computer simulations show KBOs could not have formed in today's belt. Why? There is not nearly enough material in this region to accumulate into objects hundreds and thousands of kilometers across during the solar system's life.

One theory to explain this quandary suggests the primordial Kuiper Belt had to be perhaps 50 times its present mass. Numerical simulations show the largest KBOs were well on their way to growing into large planets, perhaps something the size of Mars, Earth, or even Neptune, when something suddenly interrupted their growth. A likely culprit: the growth of "nearby" Neptune.

One effect of this "dynamical excitation" would have been that collisions became erosive, rather than accretional as they had been. Once this transition took place, the growth process would have stopped. Erosion then would have ground much of the mass in the ancient Kuiper Belt into dust. The Sun's radiation pressure subsequently would have blown this dust into interstellar space.

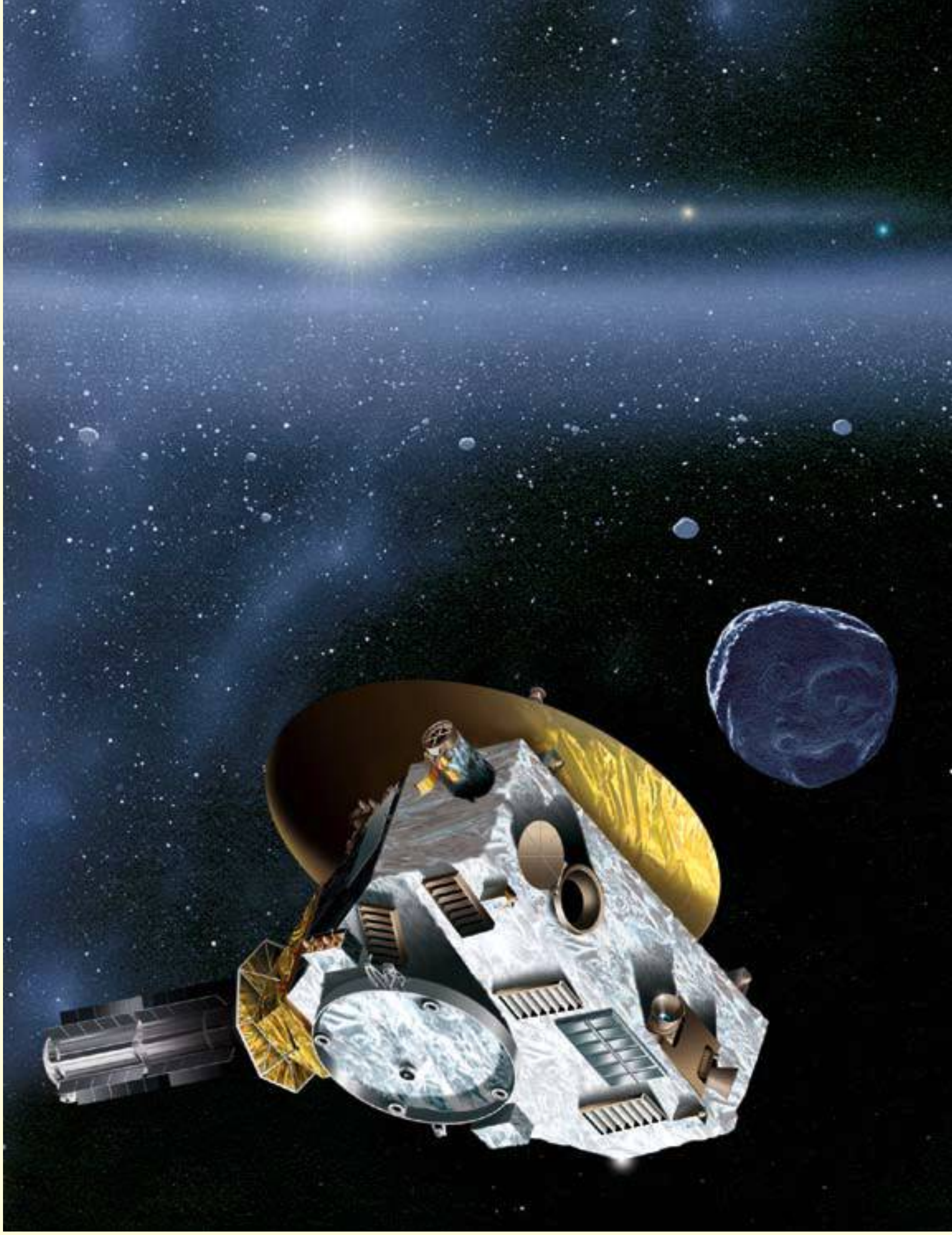
Astronomers have witnessed similar processes taking place in what appear to be Kuiper-like belts around many stars in our galaxy, including Vega and Beta Pictoris. This scenario appears to explain the lack of a large planet in the Kuiper Belt as well as the dearth of mass found there.

Other astronomers think the mismatch between the Kuiper Belt's current mass and the much larger amount required to form the bodies in it stems from the KBOs forming elsewhere. These researchers conclude the objects we now see orbiting in the 30 to 50 AU region formed closer to the Sun, in the middle zone of the solar system, where we know a huge mass of rock and ice existed when the giant planets formed.

If the KBOs developed closer to the Sun, then how did they get to their present orbits? According to some models of solar system formation, the migration of the giant planets transported the KBOs. This migration would have swept many smaller bodies from the middle zone out to the Kuiper Belt and even to the Oort Cloud beyond.

What actually happened? We do not know. In fact, both scenarios may have played a role, each responsible for some aspects of the present-day Kuiper Belt.

PLUTO AND CHARON MAKE the solar system's only true double planet — their balance point lies between them rather than inside the main body.



▲ **THE NEW HORIZONS SPACECRAFT looks back on a Kuiper Belt object shortly after its flyby. From a distance of 4.1 billion miles (6.7 billion km), the faint Sun glows inside the zodiacal dust cloud.** NASA/ESA/M. BROWN (CALTECH)

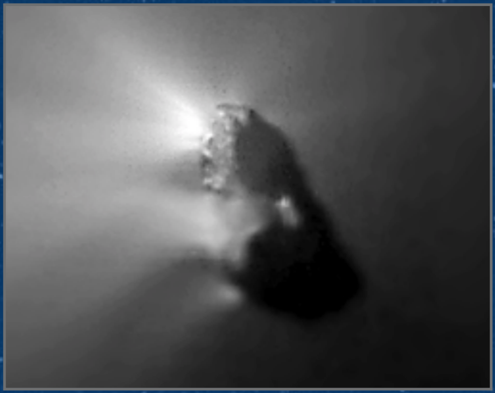
A clue to the past

Overall, the Kuiper Belt is a highly varied collection of collisional shards and dwarf planets. Owing to its strongly heterogeneous population and its nature as a collection of ancient bodies left over from the formation of the outer planets, the Kuiper Belt ranks among the most scientifically significant parts of the solar system.

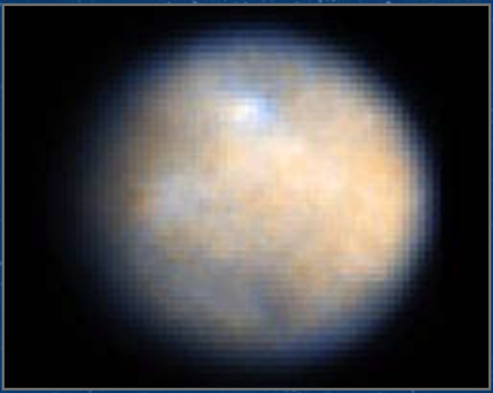
The Kuiper Belt's discovery has revolutionized scientists' view of our home planetary system in three important ways. First, it gave context to Pluto's existence, which, prior to 1992, appeared to be an oddity. Second, it provided strong links between our solar system and the kinds of debris disks seen around main sequence stars like Vega, Fomalhaut, and Beta Pictoris. Finally, it helped us realize that our planetary system contains a "third zone" — an ancient, icy disk of miniature worlds dotting the space beyond the giant planets.

The study of the Kuiper Belt remains in its infancy. Although we have learned much, we have much to learn. If we can count on anything, however, it's that the Kuiper Belt will continue to surprise. ◘

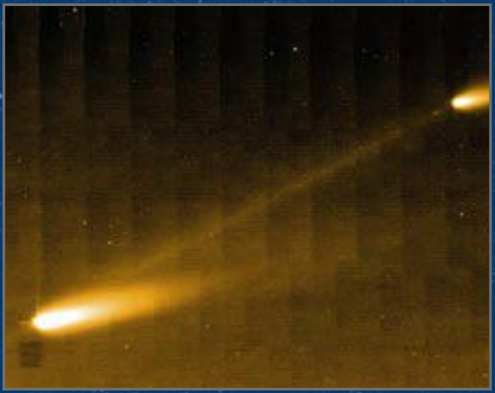
Are comets and asteroids the



▲ **DARKER THAN COAL,** the nucleus of Halley's Comet was first seen close-up in 1986 by the European Space Agency's Giotto probe. Halley is the most active comet with an orbit less than 200 years. ESA/MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH



▲ **ASTEROID 1 CERES,** the largest object in the main belt, spans 560 miles (950 kilometers). In late 2006, astronomers classified the asteroid as a dwarf planet. Ceres may have a rocky inner core, an icy mantle, and a thin, dusty outer crust. NASA/ESA



▲ **THE CRUMBLING COMET** 73P/Schwassman-Wachmann 3 cracked into four pieces in 1995; now, there are dozens. This 2006 Spitzer Space Telescope image shows the bridge of debris that connects the fragments. NASA/JPL-CALTECH/W. REACH (SSC/CALTECH)

COMET HALE-BOPP **(C/1995 01) was the most active comet in centuries. As a comet nears the Sun, ice vaporizing from its surface creates dust jets that brighten it. Gas and dust swept back by the Sun form a comet's bluish gas tail and its brighter dust tail.** TONY AND DAPHNE HALLAS

same thing?

Planetary scientists once regarded comets and asteroids as having distinct pedigrees. New studies show they may not be so different. **by Henry Hsieh**

▲ **ASTEROID 433 EROS** **measures about 21 by 8 miles (33 by 13 km). It's covered by craters, grooves, layers, house-sized boulders and other features indicating a complex history. NASA's NEAR Shoemaker mission landed on Eros in 2001.** NASA/JHUAPL

Astronomers say asteroids are inert, rocky objects that formed in the warm inner solar system. Comets, on the other hand, are active, icy visitors from the frigid depths of the outer solar system — either the Kuiper Belt, just beyond Neptune's orbit, or the more distant Oort comet cloud.

But it's not that simple. Scientists have long recognized that these definitions aren't especially clear-cut. New research verifies comets aren't as icy as once believed — and that many asteroids contain ice. The truth is, both categories comprise a population of ancient objects with a wide range of physical properties.

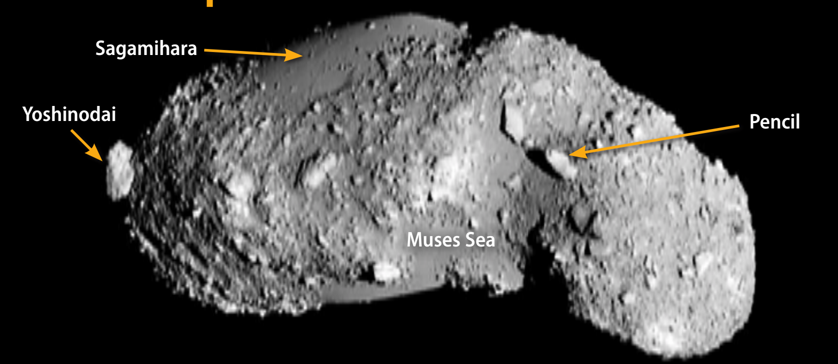
Comet vs. asteroid

Comets are distinctive celestial bodies that have dazzled humans for centuries. Indeed, they've provided the initial spark of astronomical interest in many who later became professional astronomers.

To the unaided eye, a comet's bright, fuzzy head, or coma, clearly sets it apart from pinpoint stars and planets. Tails, created from gas and dust blown off a comet's small icy body, can stretch hundreds of millions of miles into space, and they're often spectacular.

Chinese astronomers recorded the first comet observations as early as the 11th century B.C. They dubbed these showy cosmic visitors "broom stars" or "tailed stars," depending on their appearance. Throughout history, artists and chroniclers have used comets as harbingers of doom. The famous Bayeux Tapestry, which commemorates William the Conqueror's victory over

Itokawa up close



ASTEROID 25143 Itokawa has a surface like no other body yet seen. The boulder named Yoshinodai measures 160 by 72 feet (50 by 22 meters) and rises 56 feet (17m) above the surface. Gravel, not dust, covers smooth areas like Muses Sea and Sagamihara. Scientists speculate Itokawa's peculiar shape arose when two smaller rocks collided and fused, forming the 1,750-foot-wide (535m) asteroid. JAXA

STATISTICS: Ceres vs. Earth

	Ceres	Earth comparison
Mass	1.9 billion trillion pounds	0.01%
Diameter	597 miles	7.5%
Density	1.93 grams/cc	35.1%
Weight of 150-lb person	4 pounds	0.03%
Distance from Sun	257.2 million miles	276.7%
Orbital period	4.60 years	460%
Length of day	9.075 hours	37.8%

Mass: Total mass (1 billion = 10^9;1 trillion = 10^{12}); **Diameter:** Equatorial diameter; **Density:** Average density in grams per cubic centimeter (water = 1); **Distance from Sun:** Average distance; **Orbital period:** Sidereal period; **Length of day:** Average time between successive noons; **Earth comparison:** Ratio of Ceres' to Earth's value.

England's King Harold in 1066, includes Halley's Comet as an omen. Even in the late 1990s, the bright comets Hyakutake and Hale-Bopp spawned doomsday predictions.

By contrast, the history of asteroids is both brief and lackluster. Italian astronomer Giuseppe Piazzi found the first asteroid, Ceres, January 1, 1801. As is often the case with the discovery of any new phenomenon, the strange object Piazzi found created some confusion.

In his announcement, Piazzi himself dubbed the object a comet — albeit a strange one that lacked the characteristic fuzzy coma and tail of other comets. German astronomer Johann Bode immediately suspected the new object was the missing planet between Mars and Jupiter predicted by a simple arithmetic relation he promoted (now known as the Titius-Bode law).

In 1802, following the discovery of Pallas by Heinrich Wilhelm Olbers, England's William Herschel understood that these finds represented a new class of celestial object. He suggested the name "asteroid" because of their star-like appearance in a telescope.

Since then, the International Astronomical Union's Minor Planet Center has cataloged more than 300,000 asteroids. Most reside in the same region of space where Piazzi located Ceres, in the main asteroid belt between Mars and Jupiter.

Asteroids there travel mostly on nearly circular orbits lying in nearly the same plane as the solar system's major planets. Comets occupy orbits that are much more elongated than those of main-belt asteroids and often more inclined to the rest of the solar system.

Observationally, a comet's fuzzy coma distinguishes it from an asteroid. Ice contained in a small solid body (called a nucleus) changes directly from solid form to gas when exposed to the Sun's warmth. The comet's gas jets also launch dusty debris into space, and the gas and dust can become visible as a coma and tails.

Blurred boundary

In 1950, Fred Whipple at Harvard University developed the icy conglomerate — known popularly as the "dirty snowball" — model for comets. Whipple pictured comet nuclei as mostly volatile ices (water, carbon monoxide and dioxide) mixed with a bit of rocky material. This explained a variety of puzzling cometary phenomena, including tails, jets, and orbital changes resulting from the jets' rocket-like force on the nucleus.

OBJECTS THROUGHOUT THE ASTEROID BELT COULD HAVE FORMED WITH AT LEAST SOME ICE.

The trouble is, comets disagree with the model. Several space missions visited comets: the European Space Agency's Giotto spacecraft encountered Comet 1P/Halley in 1986; NASA's Deep Space 1 flew past Comet 19P/Borrelly in 2001; and in 2005 NASA's Deep Impact flew past Comet 9P/Tempel 1 and crashed a probe into it. Each mission revealed its target comet to be less icy and contain more nonvolatile material than scientists previously thought.

Because comets have limited ice reserves, they should eventually deplete all volatile material after many solar heatings. Such a comet would forever end its characteristic outbursts and look like any other space rock.

Comets may also become temporarily inactive. Gas and dust jets shut down when the comet's orbit carries it back into the outer solar system's deep freeze, where temperatures are too cold for its ice to sublimate. Also, a process called mantling can create a crust of nonvolatile matter that shields icy areas from the Sun's heat. When active comets go dormant, they become hard to distinguish from asteroids.

One might guess astronomers can tell an inactive comet from an asteroid by its orbit alone, but it's not so simple. Jets and gravitational boosts from close planetary passes can modify comet orbits. Comet 2P/Encke's orbit, which has the shortest period (3.3 years), is strongly modified by gas jets.

Worse yet, otherwise ordinary main-belt asteroids can undergo dramatic orbital changes through collisions. Even sunlight can gradually change their orbits (through the so-called Yarkovsky effect) and nudge them into gravitationally unstable regions in the solar system called dynamical resonances. These are places where asteroids can be ejected from the main belt and into planet-crossing, almost comet-like, orbits.

What further complicates the picture is the realization that asteroids aren't completely rocky.

Henry Hsieh *is a postdoctoral research fellow at Queens University in Belfast, Northern Ireland. As a graduate student at the University of Hawaii, he led the discovery of main-belt comets.*

A TRANSITION-OBJECT MENAGERIE

Many objects possess characteristics of both asteroids and comets. Here are the most prominent examples astronomers recognize.

NEAR-EARTH OBJECTS (NEOs): While we find most asteroids in the main asteroid belt between Mars and Jupiter, many also reside in near-Earth space. Most NEOs likely were ejected from the asteroid belt, but studies show this class likely includes some inactive comets, too.

HILDA ASTEROIDS: The Hilda asteroid group occurs in the outer reaches of the main asteroid belt, close to Jupiter. Spectra of these bodies show they resemble some comet nuclei.

Computer simulations suggest some comets may come from the group, although this relationship remains unconfirmed.

On the other hand, Jupiter's gravity can wrench a comet from the outer solar system into Hilda-like orbits. Confusingly, true active comets occasionally can infiltrate the group.

TROJANS: Trojan asteroids travel in two swarms that lead and follow Jupiter by 60°. Astronomers think they've occupied this position since the solar system formed. Because they lie outside the solar system's snow-line, many astronomers think the Trojans could be as icy as comets.

CENTAURS: Centaurs may be new comets transitioning from circular Kuiper-Belt orbits to elliptical comet orbits. They're located between the orbits of Jupiter and Neptune.

Astronomers have recorded comet-like outgassing from several centaurs. Such observations mean astronomers must grant the objects dual citizenship. So, the centaur Chiron is alternately identified as asteroid 2060 and Comet 95P.

DAMOCLOIDS: Named for their first-known member, the asteroid Damocles, this group includes inactive asteroid-like objects with orbits strikingly similar to Halley's Comet. This suggests the objects are inactive comets that originated in the Oort Cloud.

ASTEROIDAL METEOR STREAMS: When Earth's orbit intersects the dusty trail in a comet's wake, the number of visible meteors increases. Such a sudden enhancement is called a meteor shower.

The Perseid meteor shower each August arises from debris shed by Comet 109P/Swift-Tuttle. But some meteor showers, like December's Geminids, seem instead related to inactive asteroids. The stream responsible for the Geminids comes from asteroid 3200 Phaethon, which has never displayed comet-like activity.

MAIN-BELT COMETS: This is the most recently recognized — and perhaps, the most surprising — class of transition objects yet found. Astronomers cannot trace main-belt comets to the outer solar system. Surprisingly, they seem to be native members of the main asteroid belt.

Astronomers have identified three members so far: Comets 133P/Elst-Pizarro, P/2005 U1 (Read), and 176P/LINEAR. All display unambiguous outgassing.

This means icy objects exist today in the main belt. How this ice survived so close to the Sun for so long is an astronomical puzzle.

Like comets, many asteroids either now contain volatile ices or once did. We know this from meteorites, some of which derive from main-belt asteroids. These meteorites show minerals that form only in the presence of liquid water.

Models of the solar system's formation suggest the so-called "snow line" — the critical solar distance where temperatures were low enough for icy objects to form — could have been as close to the Sun as Mars. This implies objects throughout the asteroid belt could have started out with at least some ice.

And it gets even worse. In 2006, the University of Hawaii's David Jewitt and I identified a group of objects in asteroidlike orbits that we dub "main-belt comets."

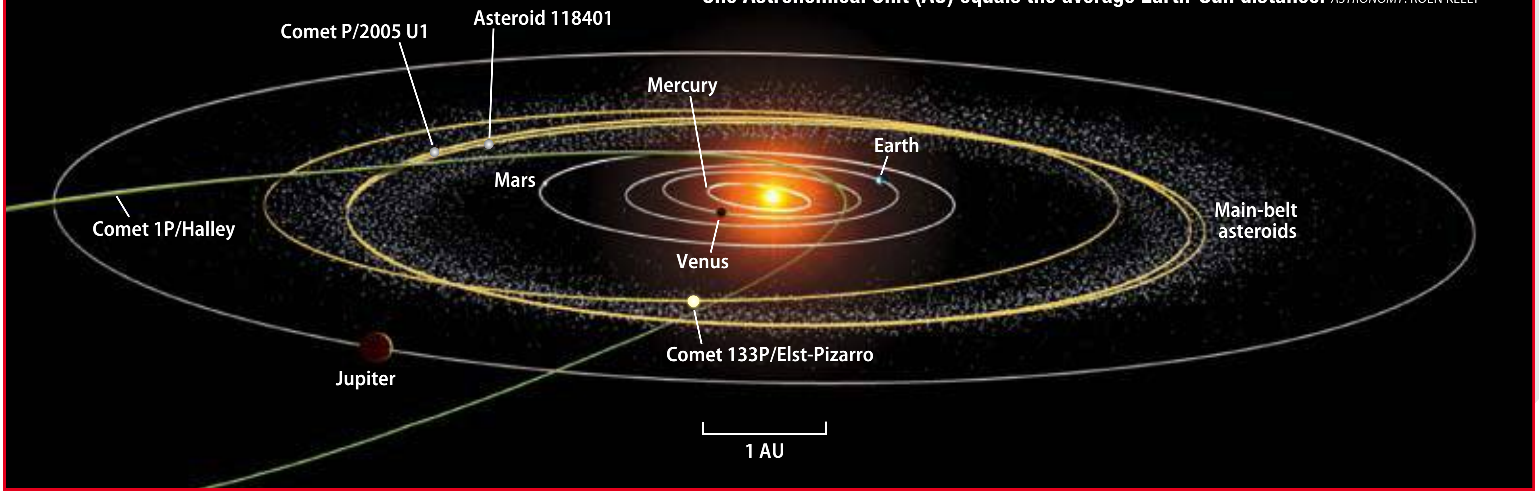
Unlike other comets, these objects appear to have formed in the warm inner solar system — inside the orbit of Jupiter, rather than out beyond Neptune. We identified three known main-belt comets: 133P/Elst-Pizarro, P/2005 U1 (Read), and 176P/LINEAR (asteroid 118401).

Orbiting completely within the main asteroid belt, these objects present a distinct contrast to other periodic comets. Simply put, they appear to have formed where we see them today. If this is true, then the main-belt comets likely contain ice with a chemical composition

COMET HYAKUTAKE (C/1996 B2) glows above Utah's Hellgate Cliffs March 26, 1996. Unlike Hale-Bopp, Hyakutake was an intrinsically faint comet, but its especially close pass to Earth made it a stunning sight. CHRISTOPHER CLEMENS

Where do asteroids and comets come from?

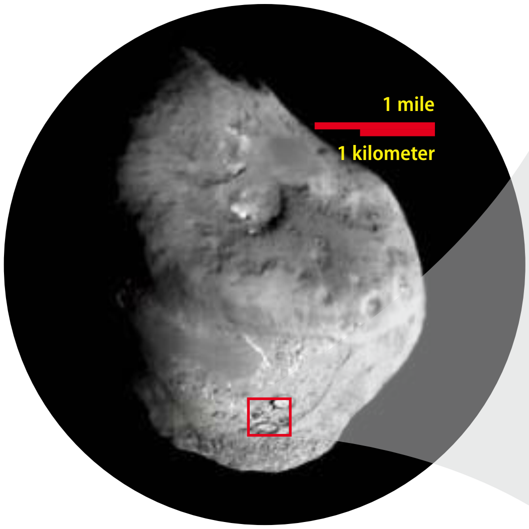
SOME MAIN-BELT ASTEROIDS show comet-like behavior. Now called main-belt comets, the nearly circular and coplanar orbits of these bodies — distinct from the elongated, tipped paths of most comets — suggest they formed where we find them today. If so, many objects in the asteroid belt could contain large quantities of ice. One Astronomical Unit (AU) equals the average Earth-Sun distance. *ASTRONOMY*: ROEN KELLY



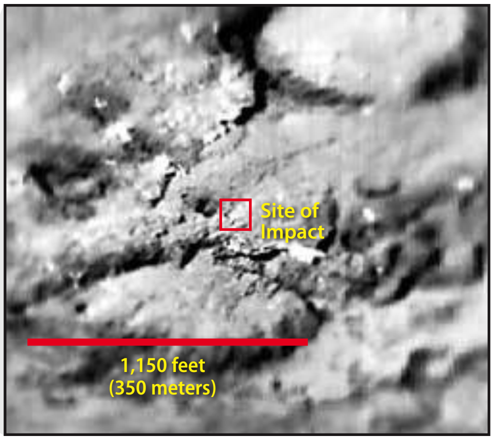
different from that of other comets. In any case, they constitute a set of transition objects between asteroids and comets.

Complex picture

Other categories also straddle the classical definitions of comets and asteroids. These transitional objects have received a great deal of attention from researchers in recent years, and for good reason. By studying these "in-between" objects, astronomers stand to gain improved understanding of precisely how the objects' physical and orbital properties relate to one another. Astronomers can unravel what took place in the young solar system by viewing it as an integrated whole.



▲ **DEEP IMPACT'S PROBE** imaged 9P/Tempel 1's surprisingly un-icy nucleus in ever-greater detail as it rushed toward the surface July 4, 2005.



▲ **THE BEST-EVER VIEW** of a comet's nucleus came to planetary scientists moments before the impactor struck. BOTH IMAGES: NASA /JPL/UMD/FRANCIS REDDY

Perhaps the most highly publicized facet of planetary science is the possibility of a comet or asteroid impact on Earth. Dealing with such a threat requires a two-pronged effort: detecting an incoming impactor, and then mitigating or eliminating the threat it poses. In-depth knowledge of the object's physical and orbital properties will be crucial to dealing with the threat.

Also, knowing the composition of comet-like, or ice-bearing, asteroids could also prove invaluable to future space missions. Near-Earth or main-belt asteroids could be mined for raw materials to facilitate longer or more ambitious space activities.

What's more, icy asteroids may have been the source for Earth's water. If planetary scientists are right that the snow-line in the young solar system was no closer than Mars, then the planets closer to the Sun, such as Earth, formed where water existed only as a tenuous vapor. If so, Earth's water likely came later, after the planet had cooled enough that surface water would not immediately vaporize and be lost to space.

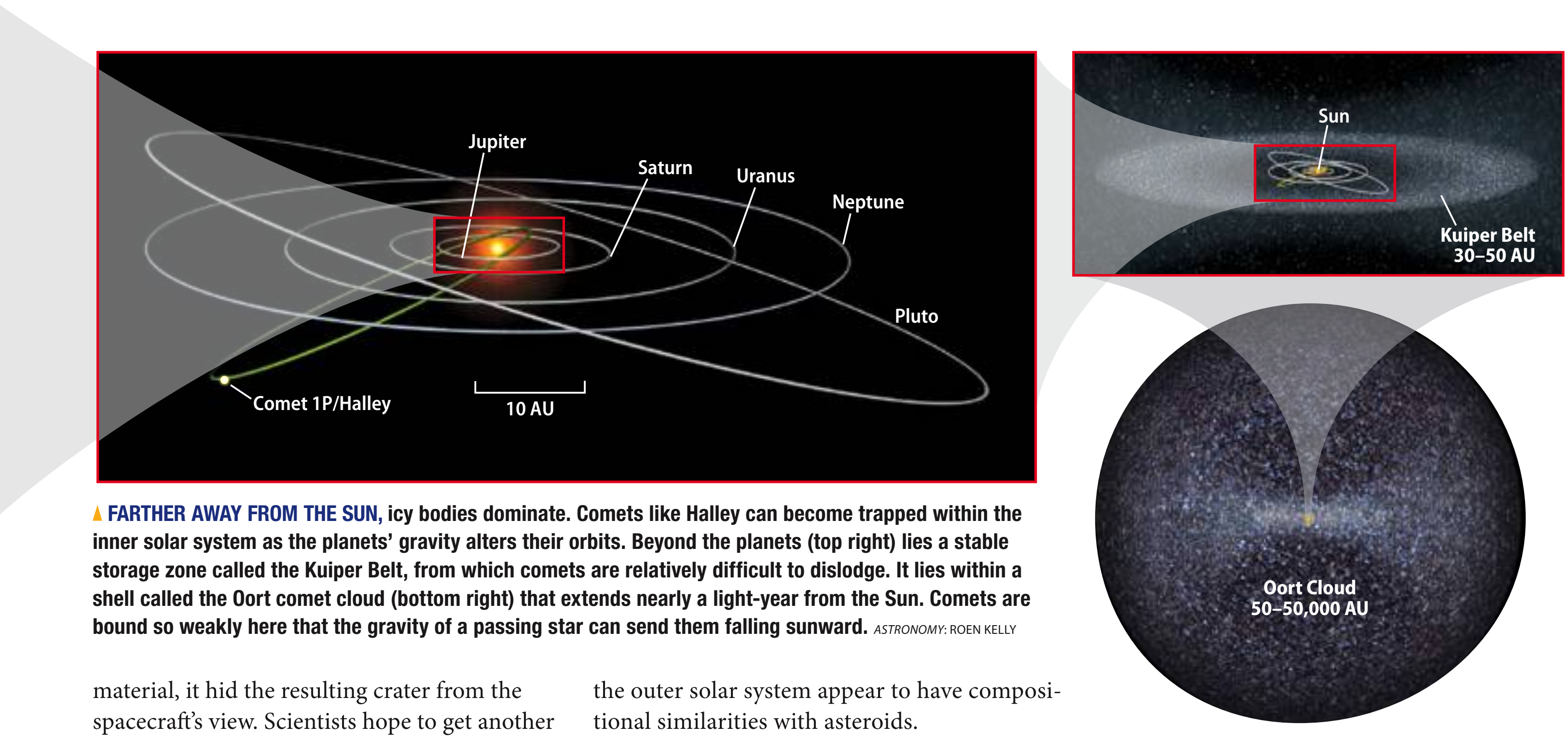
Due to their high ice content, the leading candidate for delivering Earth's water was comets. There were problems with this, however.

Simulations indicate there may not have been enough comets striking Earth during its history to supply all of the water that fills our planet's oceans. More problematically, the ratio of deuterium to hydrogen — the two most common forms of hydrogen — in ocean water is much lower than the ratio found by spacecraft measurements in three different comets. This suggests much of Earth's water had another source.

Many main-belt asteroids likely struck Earth in the past, so they're a promising alternative. Studies of meteorites presumed to have come from the main belt indicate the isotopic content of main-belt water may match Earth's oceans more closely than other comets. Ultimately, direct spacecraft measurements of the deuterium/hydrogen ratio in water-bearing asteroids will be needed to confirm this.

Spacecraft bonanza

There's much we still need to learn about comets, asteroids, and the transition objects. In 2005, NASA's Deep Impact space probe successfully struck Comet Tempel 1 with an 820-pound (370 kilograms) copper impactor. The strike blasted a hole in the comet's surface and allowed scientists to study the initial aspects of crater formation and the ensuing debris. Unfortunately, the impact kicked up so much



▲ **FARTHER AWAY FROM THE SUN,** icy bodies dominate. Comets like Halley can become trapped within the inner solar system as the planets' gravity alters their orbits. Beyond the planets (top right) lies a stable storage zone called the Kuiper Belt, from which comets are relatively difficult to dislodge. It lies within a shell called the Oort comet cloud (bottom right) that extends nearly a light-year from the Sun. Comets are bound so weakly here that the gravity of a passing star can send them falling sunward. *ASTRONOMY*: ROEN KELLY

material, it hid the resulting crater from the spacecraft's view. Scientists hope to get another look using NASA's Stardust spacecraft, which will fly by the comet in 2011.

In 2006, NASA's Stardust mission launched a sample return capsule containing dust the probe captured when it flew by Comet 81P/Wild 2. This provided scientists with the unprecedented opportunity of studying pristine comet material in Earth laboratories.

One of the more surprising findings from Deep Impact and Stardust is that the comets they studied both contain significant amounts of material that originated from the warm inner solar system. Not only do main-belt asteroids have more in common with comets than scientists once believed, but comets from the outer solar system appear to have compositional similarities with asteroids.

Future space missions promise to revolutionize our understanding of these objects. The European Space Agency's Rosetta, scheduled to visit Comet Churyumov-Gerasimenko in 2014, will go into orbit around the comet. This will allow detailed study that earlier flyby missions could not perform. Better yet, Rosetta will attempt to deploy a small spacecraft designed to make the first-ever comet landing.

As for asteroids, NASA's Dawn launched September 27, 2007, on a mission to explore the two largest asteroids, Ceres and Vesta. Dawn will ascertain the makeup of both asteroids. This will shed light on the temperature history of these bodies and on the role of water (frozen or otherwise) in their formation and evolution. Given the results of past missions, we should probably be prepared to revise our understanding of comets and asteroids once scientists fully understand the results from Rosetta and Dawn.

There are developments on the ground, too. Telescope survey projects now in development promise to give us fresh perspectives on our solar system. These include the University of Hawaii's Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), the multi-institution Large Synoptic Survey Telescope, and Lowell Observatory's Discovery Channel Telescope.

By continuously and repeatedly surveying the night sky to a much greater sensitivity than ever before, these projects will discover millions of new asteroids and thousands of new comets. Because the same projects will monitor existing asteroids at unprecedented sensitivities, I expect they'll find many more main-belt comets. We may even see traces of cometlike activity from some near-Earth asteroids, too.

Asteroids and comets deserve our attention, even if our investigations turn up more questions than answers. In the meantime, icy "broom stars" and their inactive — but maybe not so rocky — cousins will continue to sweep across the heavens, fascinating astronomers and casual stargazers alike.

Perhaps fittingly, comets and asteroids leave in their wakes as much wonder and confusion as ever. ◘

ASTEROIDS AND COMETS: THE NEW PICTURE

Evidence	Asteroids	Comets
Observational	Some main-belt "asteroids" sometimes appear to be active, just like comets.	Comets can become inactive and appear indistinguishable from asteroids.
Physical	Many asteroids probably contained ice in the past; some clearly contain volatile ices today.	Comets can eventually exhaust all volatile ices through sublimation. They have a mix of inner and outer solar system material.
Dynamical	Collisions, resonances, the Yarkovsky effect, and close planetary encounters can alter asteroid orbits.	Gas jets, resonances, and close planetary encounters can alter comet orbits.
Evolutionary	Main-belt objects most likely formed where we see them today; near-Earth "asteroids" likely include some comets from the outer solar system.	Most comets formed in the outer solar system, but main-belt comets probably formed in the asteroid belt where we see them today.

Unlocking the solar system's PAST

There's a treasure trove locked inside meteorites, rare particles older than Earth.

by David A. Kring

Scientists who study meteorites do so in a tangible way. Rather than looking at faraway objects, they actually hold the products of stars and the remnants of scattered planets in their hands. Locked within these rocks from space are tiny pieces of the solar system that predate even the planets.

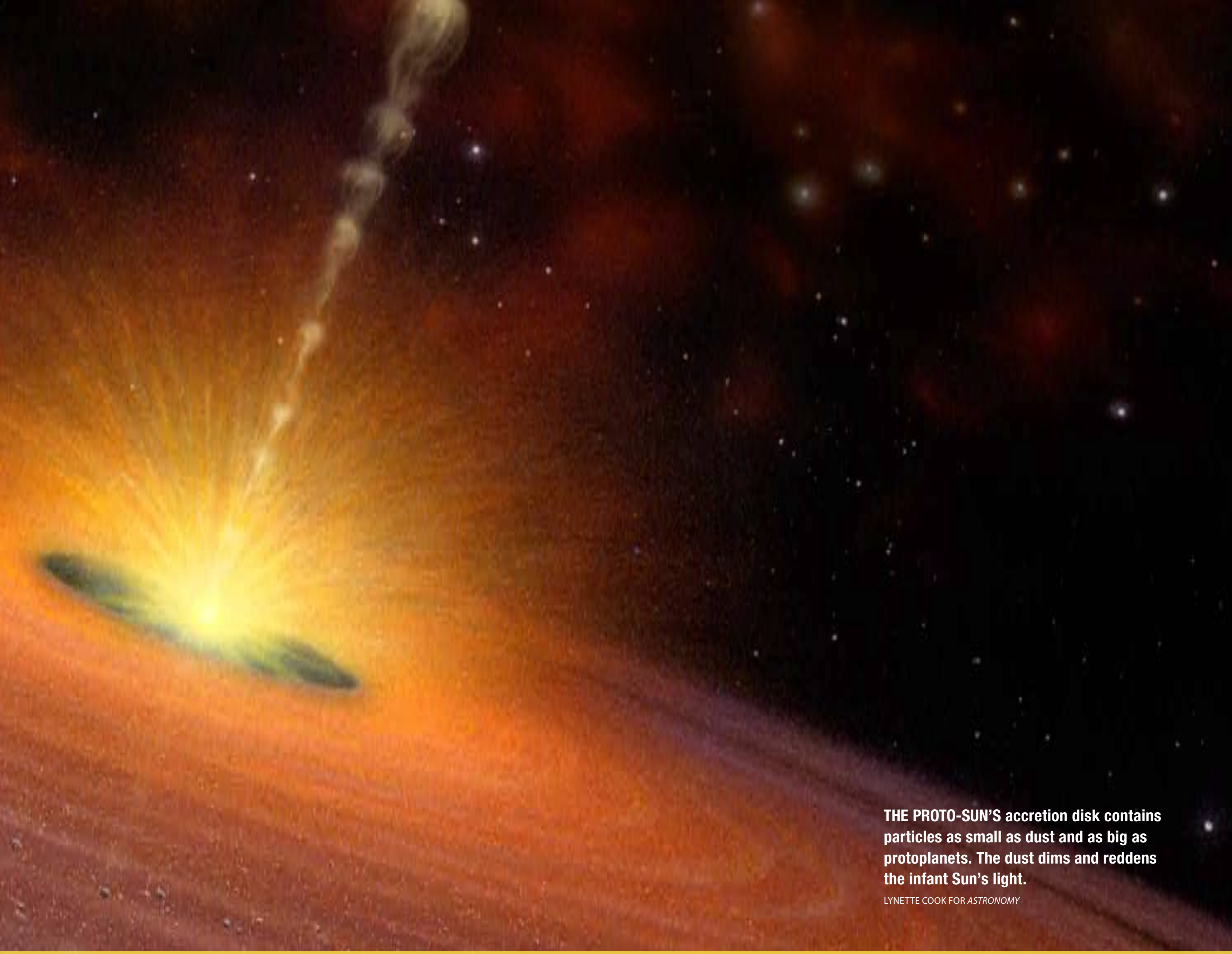
Tens of thousands of meteorites have been recovered from the far corners of our world. Although these rocks can be classified in dozens of ways, meteoriticists divide them into two main categories: those that preserve a record of the solar nebula — the growth of microscopic grains to planet-size bodies — and ones that preserve evidence of subsequent planetary processes — such as volcanism, interior melting, impacts, and fragmentation.

Clues from chondrites

Scientists tease our origins from primitive stone meteorites, 4.56 billion-year-old relics that predate Earth's formation. The jewels of these space rocks are small, millimeter-size orbs called chondrules. These minerals tell us the solid orbs were once molten droplets in space.

Olivine and pyroxene crystals, arguably the two most abundant minerals in the solar system, dominate chondrules. Their textures indicate chondrules formed from dustballs that were somehow flash-melted in episodes that exceeded 1,880° Fahrenheit (1,027° Celsius).

Some chondrules show signs of repeated exposure to brief, high-temperature conditions. These "hot zones" may have been up to a few thousand miles across, which are small on a cosmic scale. In fact, chondrules record heating events lasting as little as an hour



THE PROTO-SUN'S accretion disk contains particles as small as dust and as big as protoplanets. The dust dims and reddens the infant Sun's light.

LYNETTE COOK FOR *ASTRONOMY*

that occurred more than 4 billion years ago. Yet, despite these detailed glimpses into the origin of our planetary system, the nature of hot zones remains a mystery. Scientists have proposed transient shock waves, lightning bolts, stellar jets, and several other processes, but no one knows exactly what flash-melted the chondrules.

Chondritic meteorites hold another prize, too — objects called refractory inclusions. Refractory elements condense at high temperatures, so these inclusions also tell us of hot times in the forming solar system.

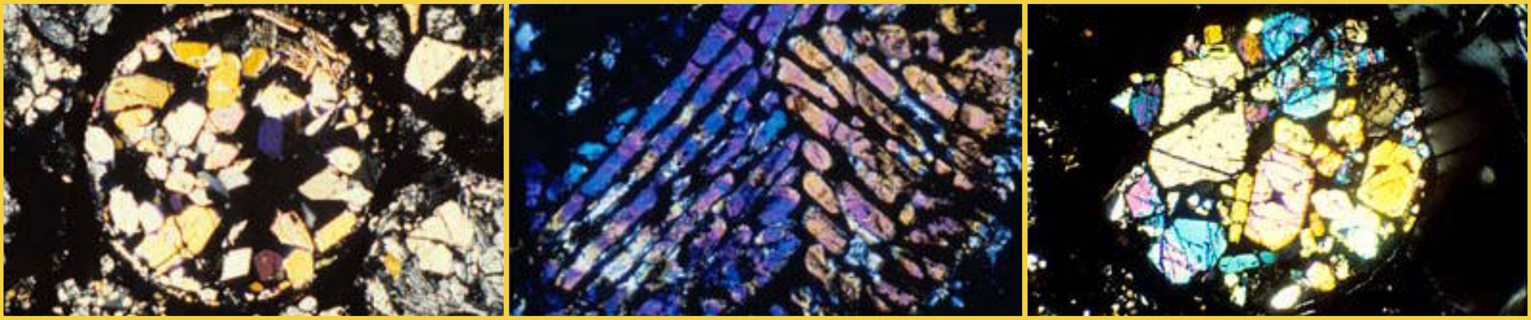
David A. Kring *is an associate professor of planetary sciences, associate professor of geosciences, the director of the NASA/University of Arizona Space Imagery Center, and the founding director of the University of Arizona Meteorite Recovery Program in Tucson, Arizona.*

Sometimes, temperatures rose so high in the solar nebula that dust evaporated, leaving refractory minerals behind. At other times, temperatures dropped so low that new dust condensed from the gas. Both materials have unusual compositions enriched in elements like calcium, aluminum, and titanium.

Planetary scientists can't say whether refractory inclusions formed in the same region of the solar nebula as the chondrules. It's possible that they give us an even earlier slice of the solar system. Some models suggest refractory inclusions formed up to 4 million years before chondrules.

From dust to planets

Eventually, space became more filled with chondrules; they bumped into each other and accreted to form larger particles. The growing particles


DAVID A. KRING

PRIMORDIAL CRYSTALS called chondrules are spherical clumps of mineral crystals that formed as molten or partially molten droplets before Earth existed. Scientists found the chondrule at left in the Semarkona meteorite, which fell in India in 1940. The center chondrule came from the primitive Mokoia meteorite, found in New Zealand in 1908. At right, Cat Mountain meteorite, found in Arizona in 1980, contained this chondrule sample.

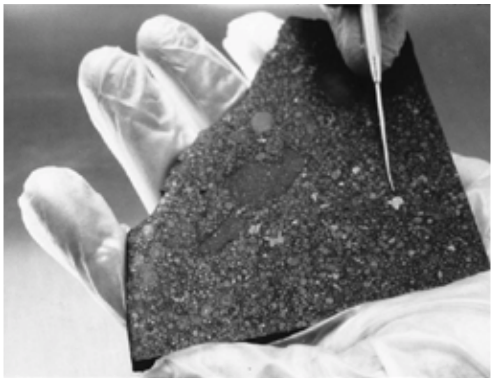
sometimes encountered refractory inclusions and lots of micron-size dust from the nebula. This material produced a fine-grained matrix between chondrules. Together, clumps of chondrules, matrix material, and refractory inclusions continued to bump into each other, forming larger objects over time. It's from these cosmic sediments that our solar system's first planet-size bodies formed.

However, the evidence paints a picture that's far from complete. Primitive meteorites come from the asteroid belt, so they preserve clues about the protoplanetary gas and dust cloud that extended from about 2 to 5 AU (an AU is the average Sun-Earth distance). This is a very selective sample in a planetary system whose total extent spans about 40 AU.

Rough neighborhood

Meteorites hold other clues about our solar system's origin as well. Although the bulk of their material formed in the solar nebula, meteorites also contain tiny pieces of interstellar matter left over from the formation of our nascent star.

Our solar system emerged from a molecular cloud rich with dust and complex of gas molecules. Although hydrogen and helium dominated the cloud, cold temperatures of about –442° F (–263° C) enabled molecules like hydrogen cyanide, water, ammonia, and formaldehyde to form. Several denser cloud cores were buried within the molecular cloud. One of those cores became gravitationally unstable and began to collapse. The core flattened and spun faster, eventually forming a disk that surrounded the proto-star that would become our Sun. Scientists call the disk the solar nebula, and most of its mass ended up in the growing star.



▲ **CLUES FROM THE SOLAR NEBULA** are locked inside the Allende slab, a meteorite that fell in Chihuahua, Mexico, in 1969. DAVID A. KRING

The collapse occurred quickly, within 100,000 years, which is a short interval when compared to geologic timescales. During that brief span, a 15,000-AU-diameter cloud core collapsed to form a 1-AU-thick solar nebula. Temperatures in the disk were hotter than in the molecular cloud core, typically over 1,000° F (538° C) in the region of the disk that would become the inner solar system.

CHONDRITES PRESERVE molecular-cloud-core dust remnants.

Primitive chondrites preserve molecular-cloud-core dust remnants. Stellar atmospheres produced these grains, so the dust identifies the types of stars that existed near where our Sun was born. This stardust contains minerals including nanodiamonds, graphite, silicon carbide, silicon nitride, corundum, hibonite, spinel, pyroxene, olivine, and amorphous glass with embedded metal and sulfide particles.

Meteorites also contain traces of nuclear reactions in stars that provide additional clues about stellar activity at the birth of our Sun. Radioactive isotopes that existed when our solar system formed — aluminum–26, iron–60, manganese–53, and iodine–129 — have now decayed, but their chemical fingerprints linger in chondritic meteorites. Taken together, stardust and these isotopes suggest the solar system formed in a seething cauldron of stellar activity and interstellar debris.

Stellar birthplaces are dynamic environments. Our own solar system's origin was probably no less dynamic or colorful. Evidence points to fast-evolving, high-mass neighbors, such as Wolf-Rayet stars and their ensuing Type II supernovae. Some may have been 15 times more massive than our Sun.

Building planets

The short-lived isotopes listed above, plus ones that are longer-lived like potassium–40, uranium–235 and –238, and thorium–232, warmed planets from the inside out as they formed in the solar nebula. The faster accretion occurred, the more short-lived isotopes contributed to the process. Each planet's size was also important. Smaller planets radiated their internal heat to space more efficiently. They have larger surface areas relative to the volume of matter.

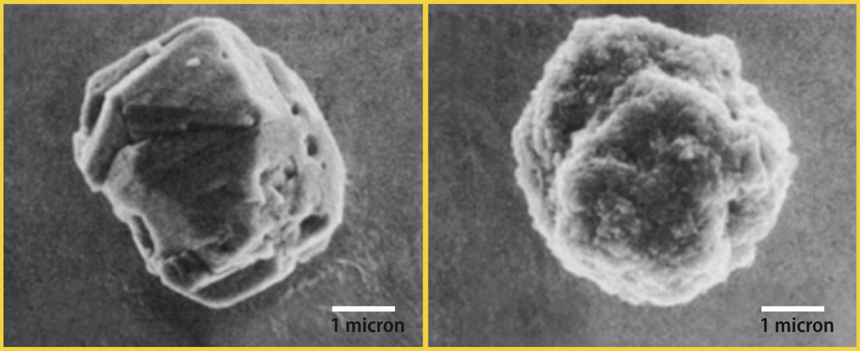
Both factors explain why some planetesimals (small bodies, most of which coalesced into planets) preserved chemical snapshots of the young solar system. Larger planets became self-insulating. They heated up to form molten objects, which destroyed clues to the past.

Some bodies fell somewhere between the two extremes. They weren't large enough to melt completely, but they did melt some. Heat altered minerals in these intermediate-size bodies, and their chemical compositions changed.

Examples of all these planetary forms can be found in meteorites. However, heat-altered samples are the most abundant, representing more than 90 percent of all recovered meteorites. Called "ordinary" chondrites, a subtype of chondrite meteorites, they are wonderful specimens of early planetary material. Scientists can easily see that planets accreted from both rocky

THE ORION NEBULA (M42) is the nearest hotbed of star formation. Here, stars form out of copious amounts of gas and dust, creating disks of debris that may make planets.

NASA/ESA/M. ROBBERTO (STScI/ESA)/HST ORION TREASURY PROJECT TEAM



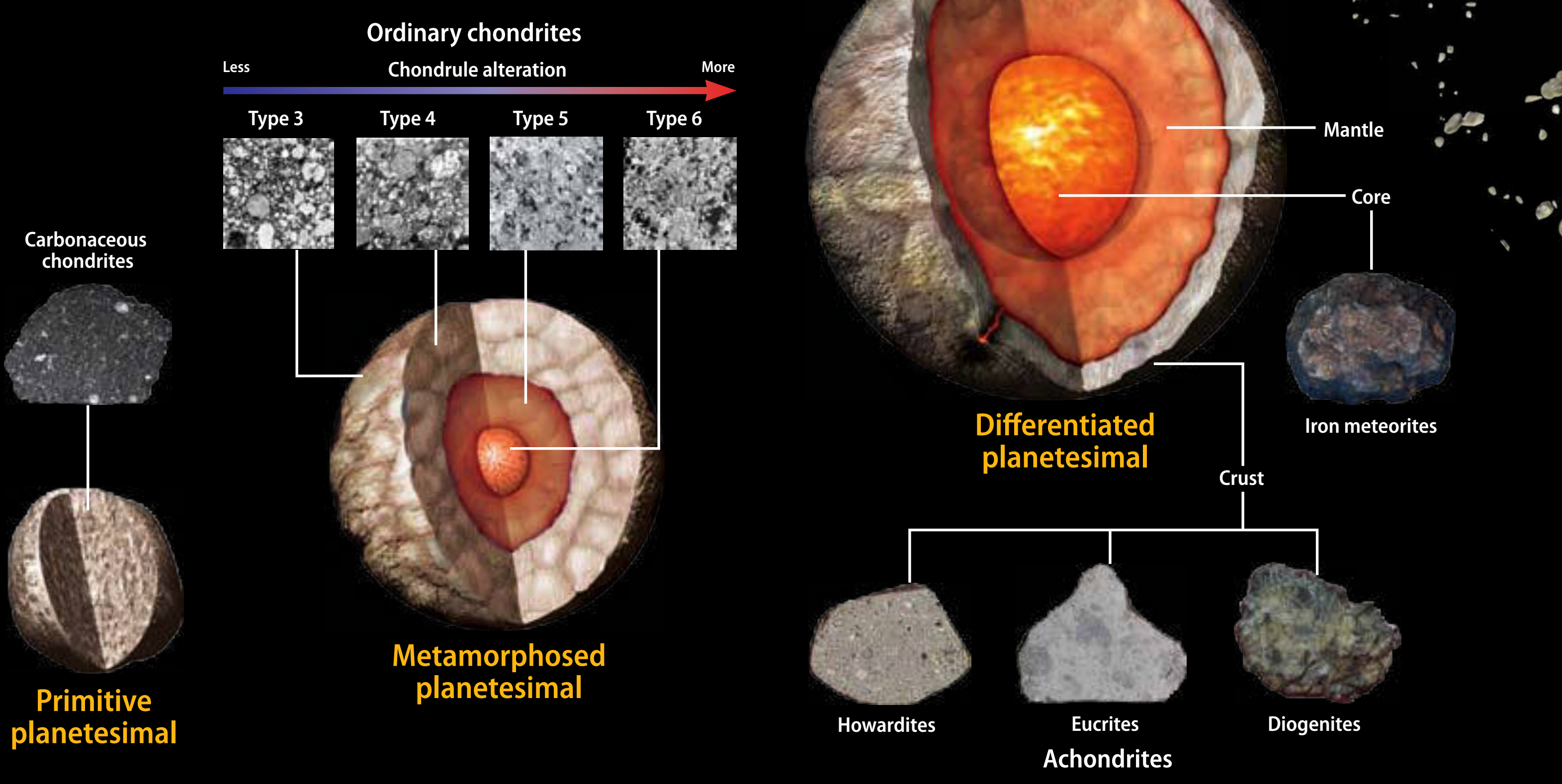
E. ANDERS/E. ZINNER

▲ STARDUST IS COMPOSED OF MICRON-SIZE GRAINS of (left) silicon carbide and (right) graphite. These tiny particles, which formed in the atmospheres of other stars before our solar system existed, are found in primitive meteorites.

NASA/RICE UNIVERSITY/C. R. O'DELL

▲ PROPLYDS ARE PROTOPLANETARY DISKS that surround the infant solar systems of other stars. These proplyds lie 1,500 light-years away in the Orion Nebula.

Meteorite origins



DIFFERENT METEORITE CLASSES reveal different parts of the solar system's history. Ordinary chondrites are meteorites that formed in metamorphosed planetesimals — bodies that partially melted and then recrystallized. Iron meteorites and achondrites (two-thirds of which originate from the asteroid 4 Vesta) come from planetesimals that experienced complete melting. These bodies differentiated into layers: an iron core, a mantle, and a crust.

ASTRONOMY: ROEN KELLY; ORDINARY CHONDRITE PHOTOS: W. R. VAN SCHMUSS AND J. A. WOOD; HOWARDITE, DIOGENITE, AND MARS PHOTOS: ROBERT HAAG; ALL OTHER IMAGES: DAVID A. KRING

and metallic components because heating enlarged the planets' metal particles. The most intensely heated planets underwent differentiation, a process in which denser metal sinks to form an iron-rich core, leaving behind a mantle and/or crust of lighter, silicate-rich material.

These clues tell us planets form fast. Analyses of isotopes in meteorite samples, plus samples from Earth, the Moon, and Mars, have put the squeeze on planetary-accretion timescales.

Scientists used to say small planets formed in 10 million years, while larger planets took 10 times longer. In contrast, several scientific groups now suggest small planets accreted, differentiated, and even produced lava flows within 3 million years. Large planets like Earth may have formed in less than 30 million years, with their cores established just 50 million years after the Sun itself.

Bumper-car evolution

The young solar system must have been an incredibly violent place. Collisions with large objects occurred frequently. One of the largest of these events appears to have occurred when a body twice the Moon's diameter, with about 10 percent of Earth's mass, hit our world. The ejected debris accreted to form the Moon.

The role of collisions in the solar system's evolution did not end with the devastating event that caused the Moon's birth. Earth and the other terrestrial planets continued to be the targets of impacting asteroids and comets.

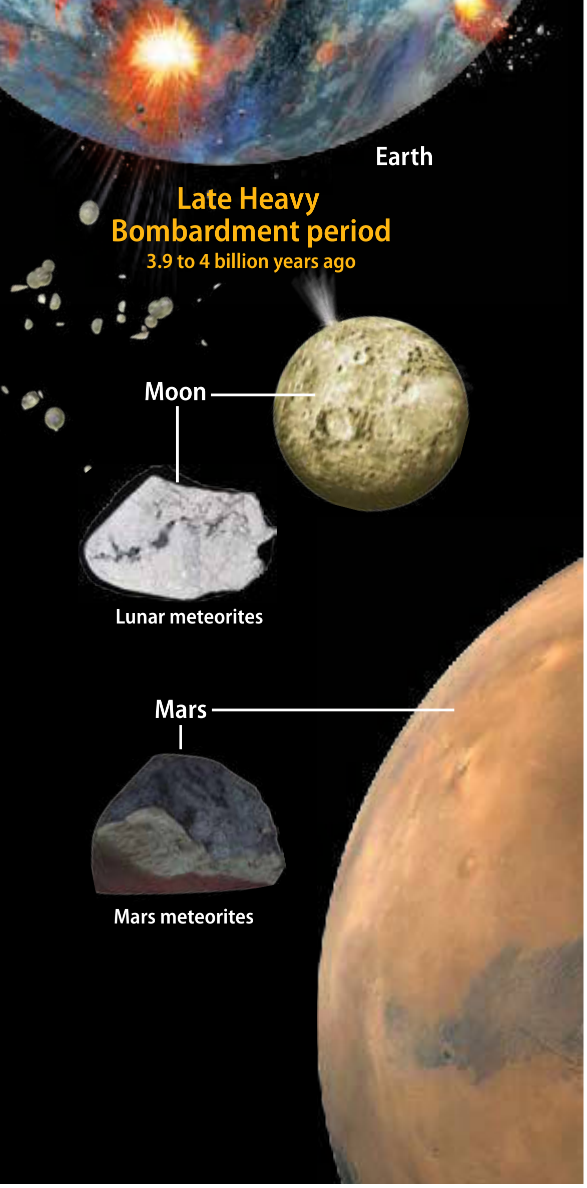
Perhaps the most famous example is the Chicxulub impact, which occurred 65 million years ago on the Yucatán peninsula. This event may have extinguished most of the life that existed during the Cretaceous Period, including the dinosaurs. Meteorites from the Moon, Mars, and asteroid belt provide new measures of how solar system collision events evolved.

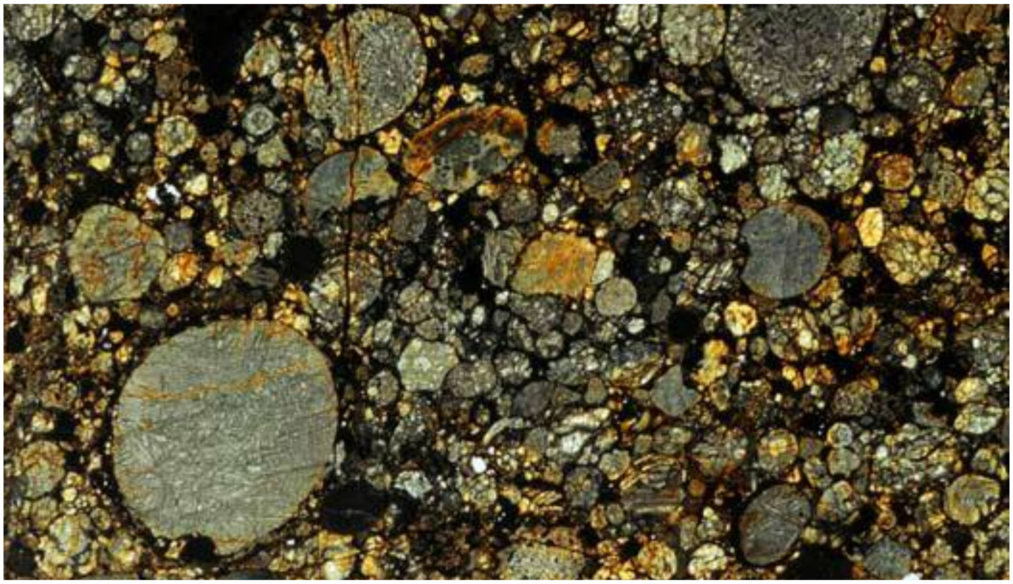
Pelted Moon

The collisional-evolution theory began with an Apollo-era study of lunar samples. When scientists analyzed the ages of samples astronauts collected, they discovered two important findings: Lunar crust was thoroughly transformed about 3.9 billion years ago. A large number of impact events at the same time produced the Moon's large — in some cases, greater than 621 miles (1,000 km) in diameter — impact basins.

These findings led to the development of the lunar-cataclysm hypothesis, in which scientists proposed the Moon (and, thus, Earth) was severely bombarded about 3.9 billion to 4 billion years ago. Skeptics, however, pointed out that the Apollo landing

◄ **DAR AL GANI 400 originated on the Moon. Classified as an achondrite stone meteorite, it was found in Libya March 10, 1998.** ROBERT HAAG





▲ **SPHERICAL CHONDRULES, which form when molten drops accrete into larger bodies, appear in this ordinary chondritic meteorite.** O. RICHARD NORTON

◄ **ALH 84001, found in Antarctica's Allan Hills ice field in 1984, sparked considerable debate in the 1990s when some scientists suggested unusual structures in the rock are martian fossils.** NASA

sites were clustered in a small area of the Moon and may have provided a biased sampling from only a couple of impact basins.

Newly discovered lunar meteorites provide a new means of testing the hypothesis of lunar cataclysm. These samples were ejected from random locations on the Moon and, thus, represent a better sampling of the lunar crust and its impact record. Analyses of melted spherules in these meteorites support the lunar-cataclysm hypothesis, which suggests there was a relative dearth of impact events about 4 billion to 4.4 billion years ago, followed by an intense bombardment about 3.9 billion to 4 billion years ago. The duration of this bombardment was 20 million to 200 million years. The end coincides with the earliest detection of life on Earth in 3.85-billion-year-old rocks.

THE LUNAR CRUST was thoroughly transformed about 3.9 billion years ago.

An analysis of martian meteorite Allan Hills 84001, the only sample from Mars' cratered highlands, also produced a 3.9-billion-year-old impact age. This suggests the lunar cataclysm should more properly be called an inner solar system cataclysm, a time when material bombarded all planetary surfaces. The source of the debris appears to be the asteroid belt.

Although the cataclysmic bombardment resurfaced Earth, it was not large enough to supply the existing water reservoir. This implies most of Earth's water already had formed and the elements needed for life already had arrived.

Environmental conditions at Earth's surface during the bombardment would have been frightful. The pounding produced more than 20,000 impact craters with diameters from 12 to 3,107 miles (20 to 5,000 km), including 40 impact basins 600 miles (1,000 km) in diameter.

It would have been a challenging, if not impossible, time for life. During the largest of these impact events, the blue seas that covered the planet may have been temporarily vaporized. These same impact events also produced vast subsurface hydrothermal systems suitable for primitive life to form. Fortunately, the bombardment was short-lived and a relatively tranquil Earth evolved, its oceans blue again.

The spike in the impact rate, approximately 500 million to 600 million years after solar system formation, is puzzling. Something unusual must have occurred to stir up the asteroid belt and fling debris throughout the inner solar system. One theory suggests the planets' gravitational influences swept through the asteroid belt, moving asteroids to cross Earth's orbit.

Could similar processes occur in other young planetary systems? The answer seems to be yes. Astronomers using the Spitzer Space Telescope have detected circumstellar debris disks created several hundred million years after their central stars formed. This implies the formation of planetary systems similar to our own.

Thus, we have come full circle. We began with meteoritic clues of how other stellar systems affected the origin and evolution of our solar system. We are now uncovering meteoritic clues that will help us better understand the origin and evolution of other stars and their planetary systems. Imagine: All of this information can be held in the palm of your hand. ◘

Weather report

What shapes planetary atmospheres?

Earth, Mars, Venus, and Saturn's moon Titan have substantial yet different atmospheres.

by Timothy Dowling

Our solar system contains an amazing diversity of atmospheres — a full dozen, if you count the Sun's. We experience Earth's "ocean of air," unique for its high oxygen content and agreeable temperature, with every breath we take.

But several worlds — Venus, Mars, and Saturn's moon Titan — host thick atmospheres, and in many respects they resemble Earth's. So why is our planet's air so thick and temperate, while Venus' is oppressively thick and Mars' barely exists at all? Understanding why they're so different gives researchers a proving ground for testing theories on how weather forms and evolves.

Meteorology began on Earth as an ancient art. Today, it brings together high-resolution satellite imagery and the world's fastest computers to solve practical problems involving public safety, agriculture, and commerce.

During the past 50 years, as meteorologists worked to understand terrestrial weather, planetary scientists have amassed a remarkable volume of atmospheric data using flyby spacecraft, orbiting satellites, and entry probes. New research lets meteorologists extend their knowledge to the solar system's other worlds.

Atmospheric scientists divide their time between operational meteorology — devising ways to improve day-to-day weather forecasts — and process meteorology, a branch that explores the fundamental workings of some of nature's most complicated processes. These include how pockets of warm, moist air rise to transfer energy, how fluids of different temperature and densities interact, and how electromagnetic radiation drives weather and climate.

Spin and Sun

Two factors conspire to whip up a planet's winds: rotation and solar energy. Rapid rotation provides the energy for cyclonic storms, such as terrestrial hurricanes or Jupiter's Great Red Spot (which is actually an anti-cyclone, or high-pressure zone). On gas-giant planets, where the atmosphere never interacts with a solid surface,

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Timothy Dowling *is the director of the Comparative Planetology Laboratory at the University of Louisville in Kentucky.*

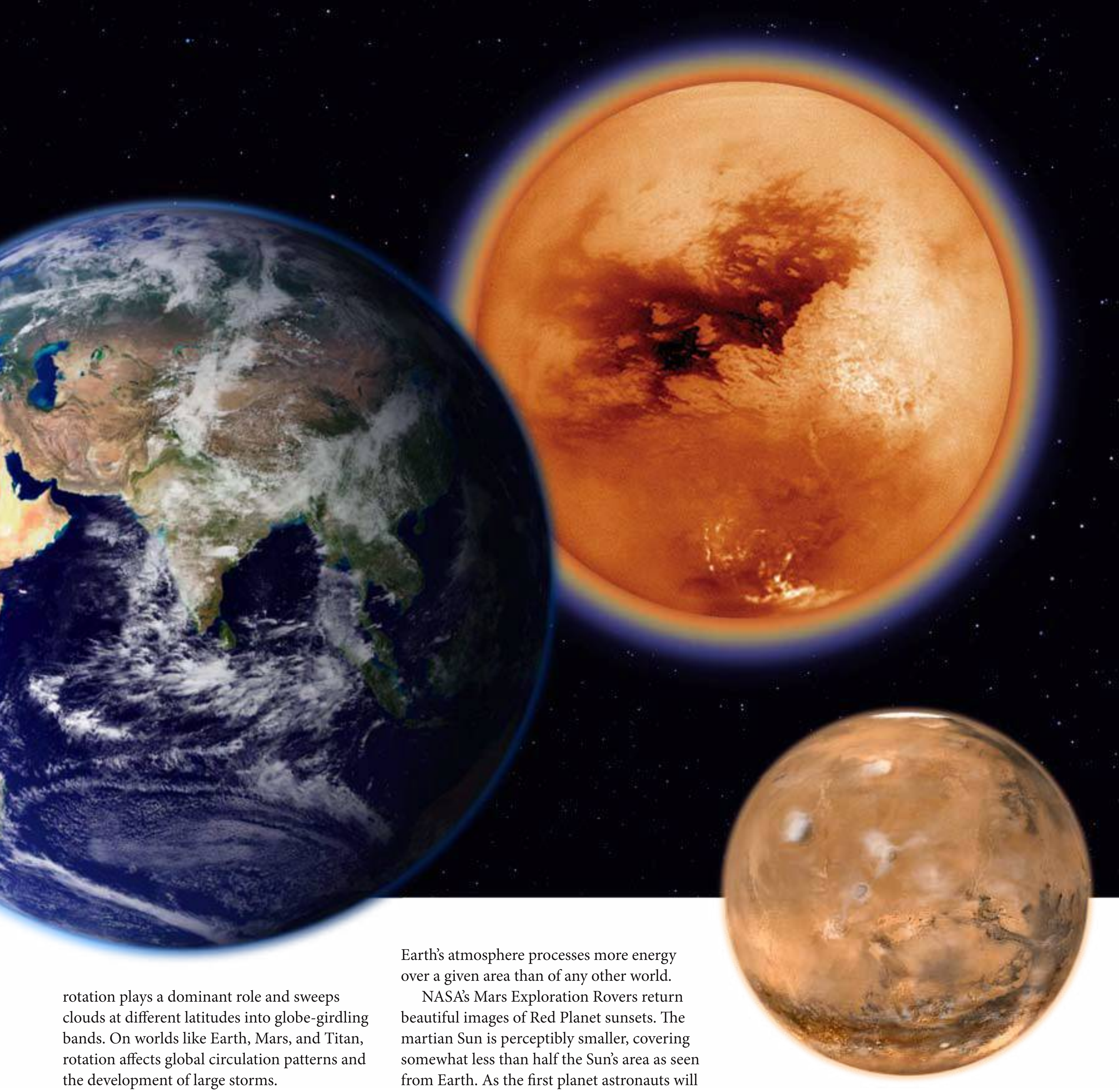
rotation plays a dominant role and sweeps clouds at different latitudes into globe-girdling bands. On worlds like Earth, Mars, and Titan, rotation affects global circulation patterns and the development of large storms.

Energy from the Sun varies with a planet's distance from it. If you could glimpse the Sun through Venus' thick global cloud deck, it would appear 40-percent larger than it does from Earth.

But the forecast for Venus is perpetual overcast. The clouds, formed by sulfuric-acid (H_2SO_4) droplets, are so reflective that, despite Venus' closer proximity to our star, Earth's surface actually receives more sunlight. In fact, Earth's atmosphere processes more energy over a given area than of any other world.

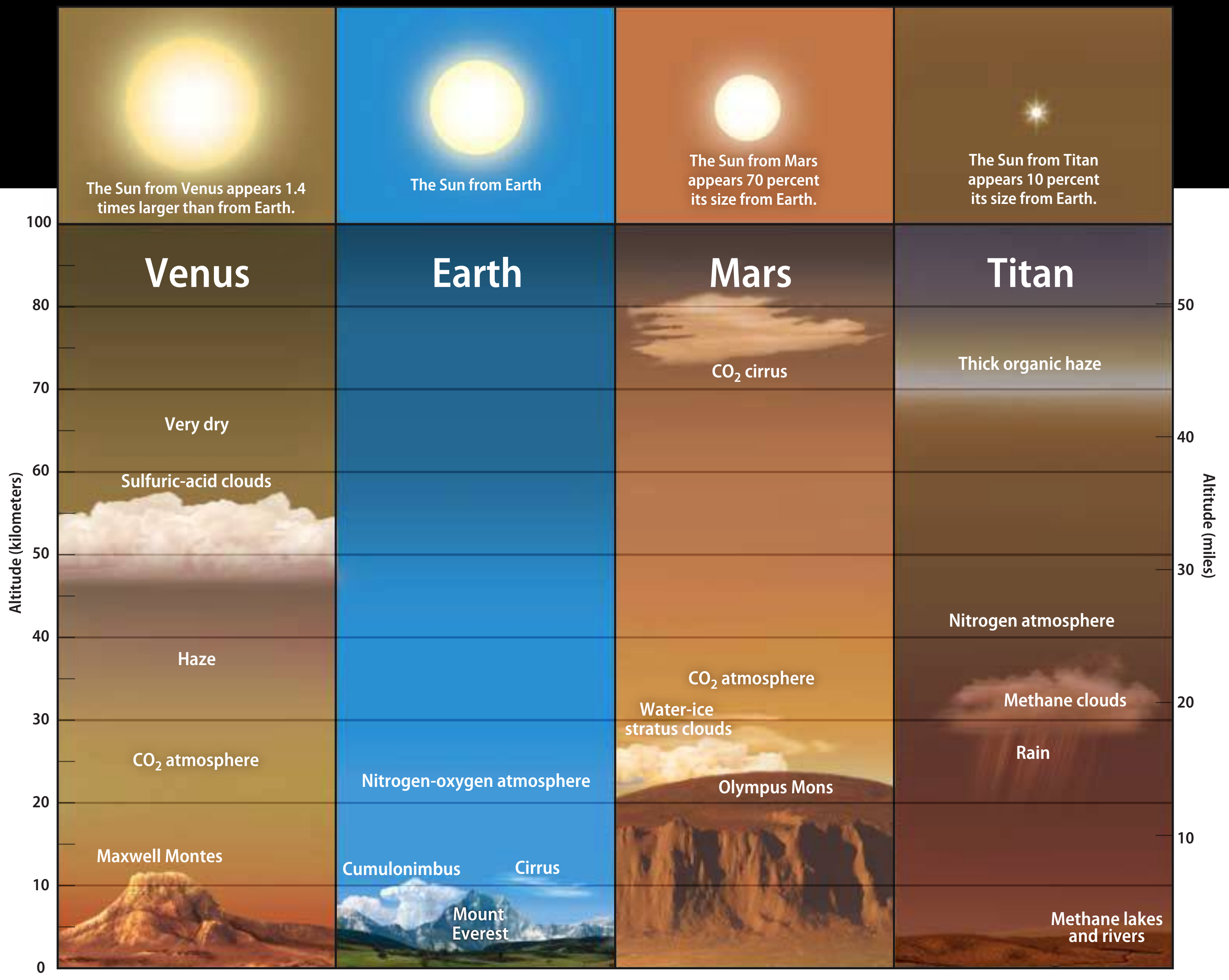
NASA's Mars Exploration Rovers return beautiful images of Red Planet sunsets. The martian Sun is perceptibly smaller, covering somewhat less than half the Sun's area as seen from Earth. As the first planet astronauts will explore, Mars is host to the first alien weather systems humans will experience.

The planet's famous dust storms are the primary meteorological hazard facing future astronauts. These ferocious storms can envelop the whole planet. Scientists don't understand what triggers regional martian dust storms, let alone why some of these systems turn into planet-eating monsters while others fade away peacefully. Predicting the weather on other planets is



▲ **THE SOLAR SYSTEM'S TERRESTRIAL WORLDS host a wide range of atmospheres. Clouds made from water vapor and ice crystals fill Earth's skies. Venus' dense atmosphere keeps the surface oven hot. Giant mountains on Mars create clouds as winds force air over them. On Titan, a frigid analog of Earth, methane rain pools into lakes and flows across the terrain in rivers.** EARTH: NASA EARTH OBSERVATORY/NASA GODDARD SPACE FLIGHT CENTER; VENUS: NASA/JPL; MARS: NASA/JPL/MSSS; TITAN: NASA/JPL/SSI

Planetary atmospheres compared


The Sun from Venus appears 1.4 times larger than from Earth.
The Sun from Earth
The Sun from Mars appears 70 percent its size from Earth.
The Sun from Titan appears 10 percent its size from Earth.
Venus
Earth
Mars
Titan
Altitude (kilometers)
100
80
70
60
50
40
30
20
10
0
Altitude (miles)
50
40
30
20
10
Very dry
Sulfuric-acid clouds
Haze
CO_2 atmosphere
Maxwell Montes
Nitrogen-oxygen atmosphere
Cumulonimbus
Cirrus
Mount Everest
CO_2 cirrus
CO_2 atmosphere
Water-ice stratus clouds
Olympus Mons
Thick organic haze
Nitrogen atmosphere
Methane clouds
Rain
Methane lakes and rivers

▲ **THIS CHART SHOWS compares atmospheric slices of three planets and one moon. Earth and Titan have nitrogen-based air, while Venus and Mars have carbon-dioxide atmospheres. The diversity of cloud altitudes and compositions illuminates the broad range of planetary conditions. The Sun's apparent size is markedly different on each world.** *ASTRONOMY*: ROEN KELLY, AFTER TIMOTHY DOWLING

an emerging field, but it's a challenge meteorologists must meet in the next 2 decades.

Farther out, at Saturn's moon Titan, we encounter a cold atmosphere half again as thick as Earth's. At Titan, astronauts would see the Sun as a tiny but brilliant disk — and to see even this, they'd have to fly above a thick, global haze.

Comparing atmospheres

Accounting for each atmosphere's basic physical characteristics — size, surface pressure, and the planet's rotation rate — it's clear the solar system contains no identical twins.

We can picture each of these parameters as one axis of a cube that contains possible values of size, pressure, and rotation. Venus and Mars occupy opposite corners in this size-pressure-rotation space, while Earth and Titan roost near opposite edges. By studying atmospheres in this way, scientists are beginning to see some common principles.

One important factor is an atmosphere's ability to retain heat that would otherwise radiate away at infrared wavelengths. This is the so-called greenhouse effect.

On Venus, which has a carbon-dioxide (CO_2) atmosphere 90 times denser than Earth's, this process warms the planet's surface to a temperature 720° Fahrenheit (400° Celsius) higher than it would be without an atmosphere. For comparison, Earth's atmosphere boosts its temperature by 54° F (12° C). For Mars and its thin CO_2 atmosphere, the greenhouse bonus drops to just 5° F (3° C).

Earth holds about as much carbon dioxide as does Venus, but on our planet the gas is bound into rocks. If these rocks suddenly released the gas, Earth's surface soon would be toast: Venus' surface is hotter than an oven.

Weather on Mars, which lacks the towering, water-rich thunderstorms of Earth, is undeniably alien to our experience. Winter brings ground frost to Mars and increases the winter hemisphere's polar ice cap, while its opposite number shrinks in the summer heat. As much

Earth and Titan are the only small planetary bodies that experience significant rainfall.

▲ **ON MAY 19, 2005, NASA's Mars Exploration Rover Spirit captured this sunset over the rim of Gusev Crater some 50 miles (80 km) away. The bluish tint, caused by light scattering off of airborne dust particles, would be visible to human eyes.** NASA/JPL-CALTECH/TEXAS A & M UNIV./CORNELL UNIV.

as 25 percent of the martian atmosphere freezes onto the winter cap.

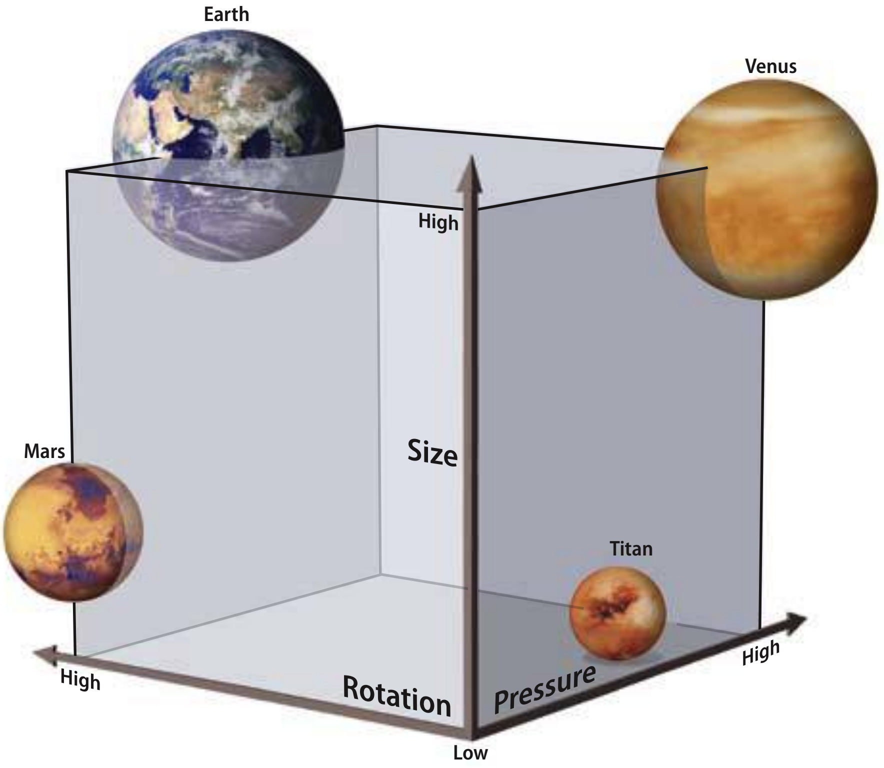
Because Mars' atmosphere and polar caps are made of CO_2, this seasonal shift induces a pole-to-pole breeze called a condensation flow. This process has no Earthly analogy, but it occurs on Neptune's moon Triton and other icy bodies at the solar system's fringes.

On Mars, thin water-ice cirrus clouds cling to the planet's tallest peaks. Higher up, we find wispy cirrus clouds made of frozen CO_2. These are the solar system's highest-altitude clouds.

Earth versus Titan

Of all the planetary environments we know, none shares more similarities with Earth than Saturn's moon Titan. At first, the differences seem more important. Although Titan is the solar system's second-largest moon, it's only 40 percent of Earth's size. Titan is nearly 10 times farther from the Sun, so a given area receives only 1-percent as much solar energy as it would on Earth. The surface temperature hovers near −290° F (−179° C).

Atmospheres in a box



▲ **EARTH'S ATMOSPHERE shares common features with those of Venus, Mars, and Titan, but no two planetary bodies repeat the basic characteristics of size, surface pressure, and planetary rotation rate. These differences help planetary meteorologists understand the common factors that drive all weather.**

ASTRONOMY: ROEN KELLY, AFTER TIMOTHY DOWLING

But the most abundant element in both atmospheres is nitrogen, and they have similar surface pressures. In fact, Titan's is actually 50-percent greater than Earth's. Sunlight at the top of Titan's atmosphere produces a thick haze of organic molecules thought to be chemically similar to material formed before life arose on Earth. Both atmospheres host clouds, but while Earth's form out of water droplets and ice crystals, Titan's arise from methane droplets.

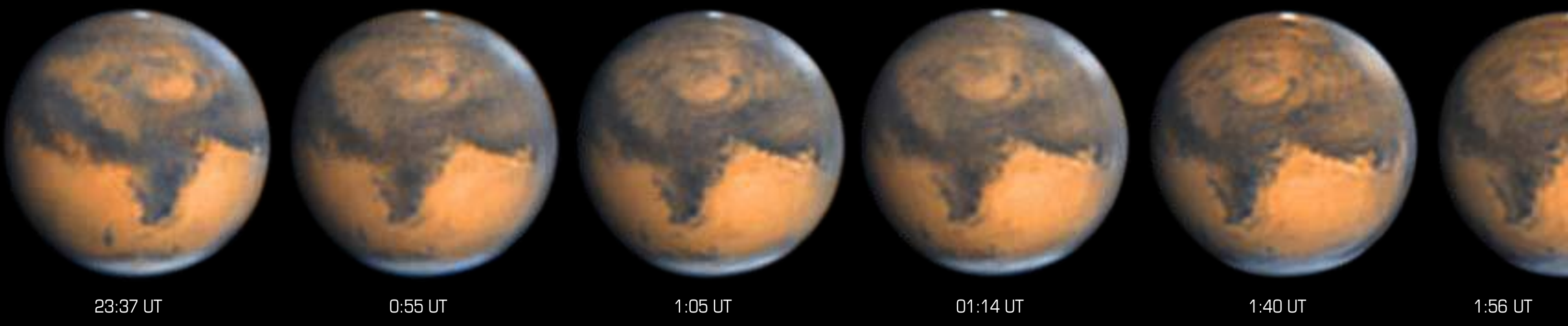
Earth and Titan are the only small planetary bodies that experience significant rainfall and surface hydrology, including active lakes and rivers. Images from the European Space Agency's Huygens probe, which landed in January 2005, shows gullies cut in Titan's surface by flows of liquid methane. These features look remarkably similar to river erosion on Earth.

Out of this world

With a single high-resolution image of a planet's clouds, scientists can tell if a planet spins quickly. From that, they then can deduce the atmosphere's temperature, pressure, chemical makeup, and other important parameters by extending concepts first learned on Earth.

One day, perhaps not too far in the future, planetary scientists will apply these principles to data from a truly alien world — one that orbits another star.

Astronomers have cataloged hundreds of planets beyond the solar system. Most are gas giants like Jupiter and Saturn, but a growing number are less massive than Neptune. Worlds this size are on the cusp: They could be either gas giants or rocky worlds like ours. Someday, planetary scientists will work up a weather forecast for Earth's twin.



How to observe

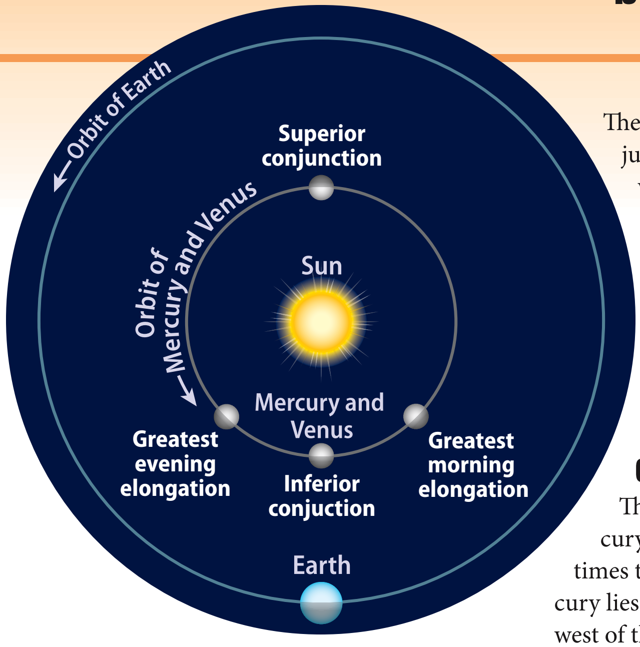
Even a small telescope will let you target the other worlds in our solar system. You'll be surprised by how much you'll see.

by Michael E. Bakich

The other planets of our solar system aren't just targets for spacecraft. They're also worlds you can observe. Even a small telescope will reveal details on the giant planets. Through a medium-size scope, you'll see Venus, Mars, Jupiter, and Saturn change on a nightly basis. And you won't need a dark sky to do so. Even under city lights, the planets provide easy targets you can watch.

Observing Mercury

Through a telescope, you can detect Mercury's phases, but details are scant. The best times to spot this elusive orb are when Mercury lies at one of its elongations, either farthest west of the Sun in the eastern morning sky or farthest east of the Sun in the evening sky.


Orbit of Earth
Superior conjunction
Orbit of Mercury and Venus
Sun
Mercury and Venus
Greatest evening elongation
Greatest morning elongation
Inferior conjuction
Earth

▲ **MERCURY AND VENUS ORBIT CLOSER to the Sun than Earth. At greatest evening elongation, we see each planet farthest east of the Sun. When at greatest morning elongation, the planets lie farthest west of the Sun.** *ASTRONOMY*: ROEN KELLY

Most good views of Mercury occur at midday, when the planet sits high in the sky. Be careful never to point your telescope at the Sun. If you can locate Mercury, use a yellow or orange filter to cut down the sky's blue light.

Observing Venus

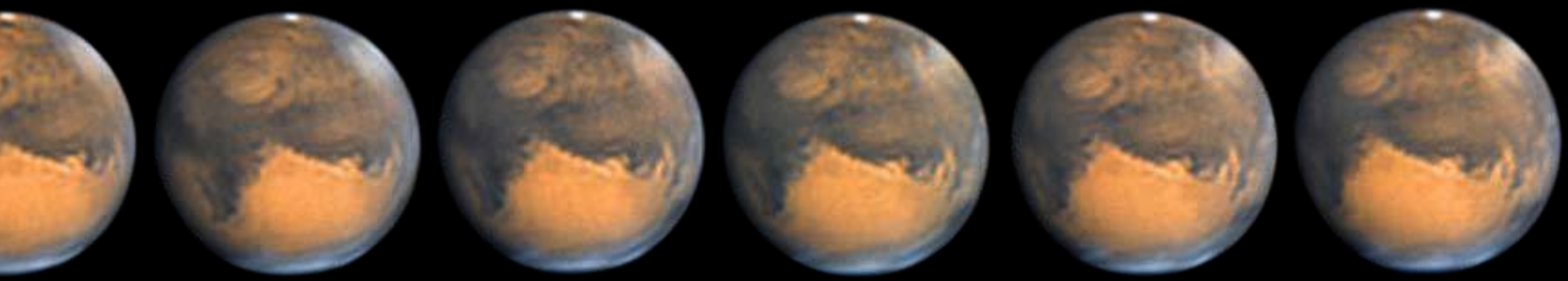
Venus is easier to observe than Mercury. Astronomers routinely follow its phases, along with size changes — a feature easier to observe with Venus than Mercury. While Mercury looks twice as big when between Earth and the Sun than it does when it lies on the far side of the Sun, Venus is more than 6 times larger. Daytime observations of Venus are also easier than those of Mercury because Venus shines brighter and can lie farther from the Sun.

Features in Venus' atmosphere range from dusty shadings to bright spots. You may be able to spot the most famous through a #47 (violet) filter. This filter doesn't allow much light through, so use at least an 8-inch telescope. Look for an immense C- or Y-shaped feature centered on the planet's equator.

Observing Mars

Mars and Earth are closest once every 26 months, but don't wait for the Red Planet to reach maximum size before you start observing it. As long as Mars' atmosphere is transparent, you'll see detail several months before and after opposition (when Mars rises at sunset, usually within a week of closest approach).

Use high magnifications to observe Mars, right up to the limit of the atmosphere's steadi-



2:17 UT

2:49 UT

3:00 UT

3:12 UT

3:31 UT

the planets

▲ **THIS SERIES OF IMAGES covering nearly 4 hours captured a large dust cloud above Mars' Argyre region. The dust (the bright, hazy region in the upper right) is easiest to see in the last three images. Where the sky was steady, observers with 4-inch telescopes viewed this event.** DAMIAN PEACH

ness. Concentrate on a small area or a single feature. Don't try to observe the entire disk or dart your gaze from one feature to another.

Mars' atmosphere features several cloud types. Seasonal clouds occur because of heating and cooling. Discrete clouds are localized and get carried along as the planet rotates.

Orographic clouds are water clouds created by wind passing over martian mountains and volcanos. To view orographic clouds, use a #80A (blue) or #47 (violet) filter. For the low-altitude ones, a #58 (green) works better.

You also can observe morning and evening clouds. These bright, isolated patches of surface fog appear at sunrise and sunset. Evening clouds are generally larger and more numerous. For the best views, use a blue or violet filter.

Observing Jupiter

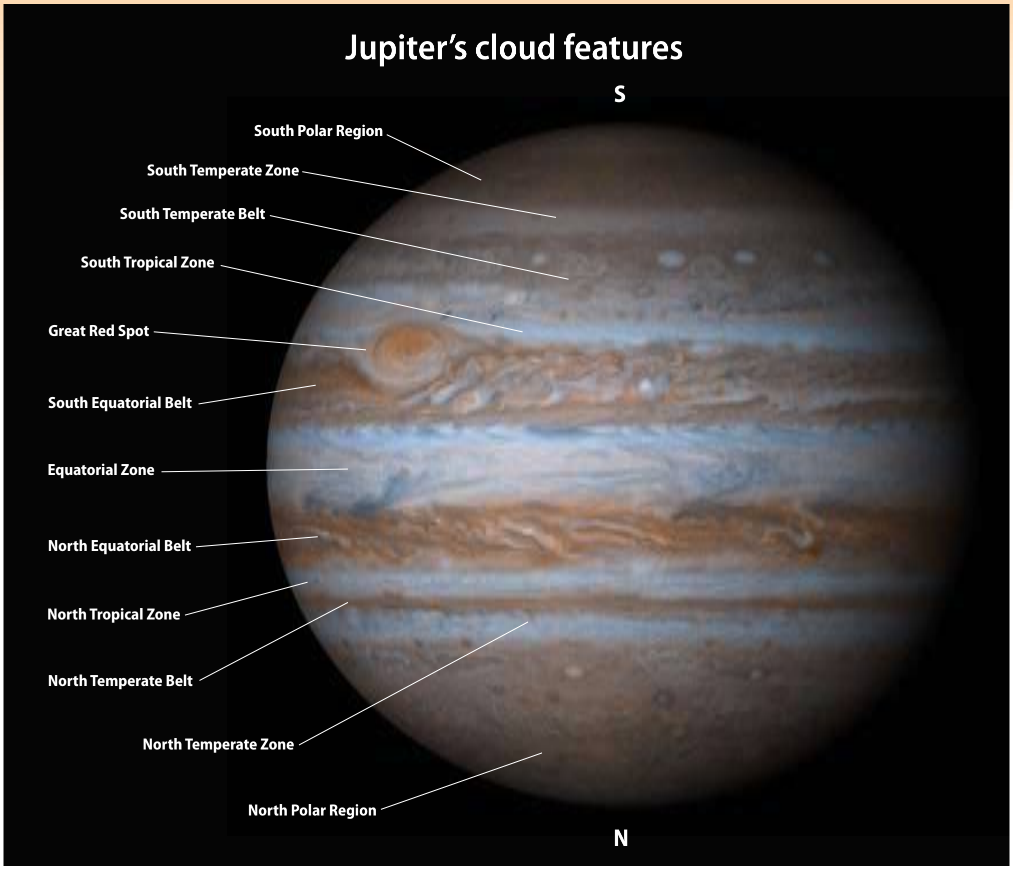
Next to the Sun and the Moon, the celestial object with the greatest detail is Jupiter. Even small scopes show several dark stripes — the North and South Equatorial Belts — flanking the giant planet's equator.

Watching Jupiter nightly can be rewarding. In addition to the changing positions of its four largest moons, the planet's rotation brings nearly all of its visible area into view in a single night. Be sure to target the Great Red Spot.

A #38A (blue) filter will enhance the planet's bright belts. Blue filters also sharpen bright cloud features. A #23A (red) filter brings out features along Jupiter's equator and sharpens contrast in the major belts.

Moving moons

Four events are possible involving Jupiter and its four large moons. An eclipse occurs when a


Jupiter's cloud features
S
South Polar Region
South Temperate Zone
South Temperate Belt
South Tropical Zone
Great Red Spot
South Equatorial Belt
Equatorial Zone
North Equatorial Belt
North Tropical Zone
North Temperate Belt
North Temperate Zone
North Polar Region
N

► **JUPITER'S ATMOSPHERE divides into dark areas, called belts, and lighter ones, called bands or zones. Within these regions, you'll find details you can observe through small telescopes.** NASA

HOW TO USE FILTERS

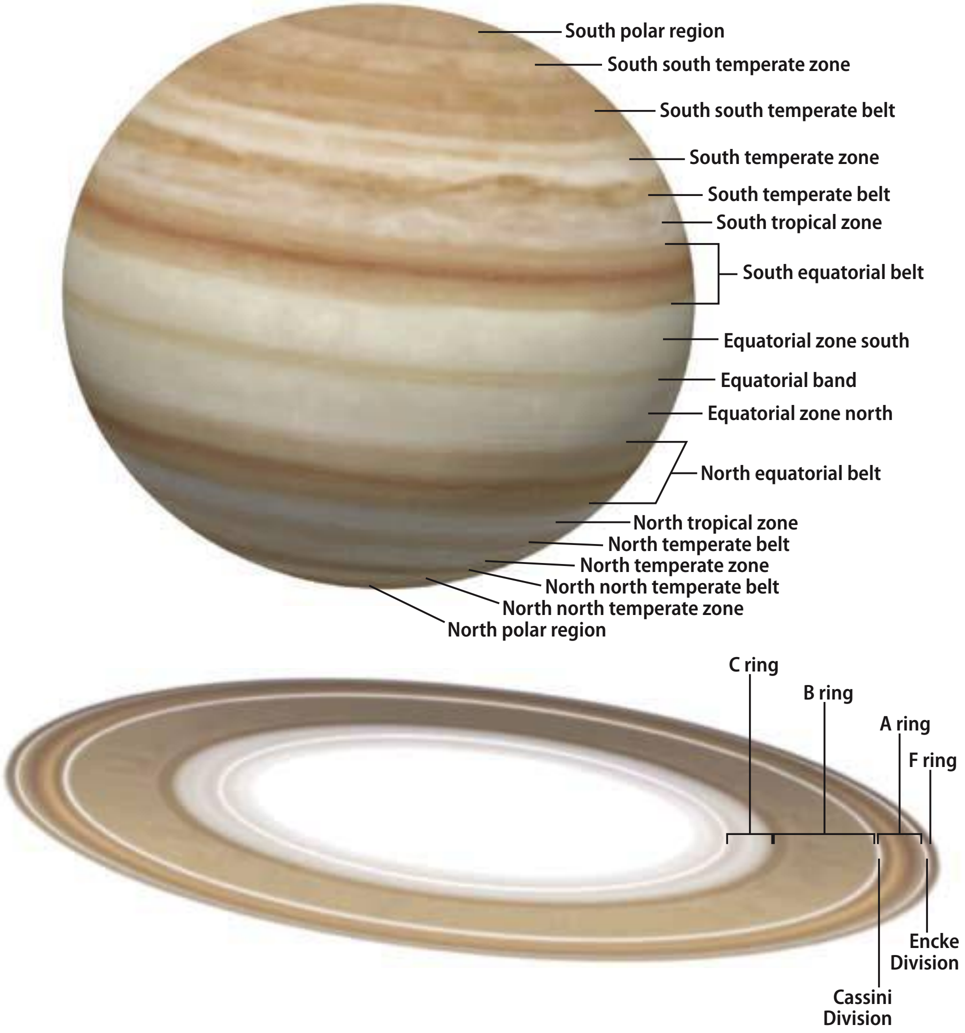
For the planets, use color filters — but don't let the name fool you. Filters don't add or show colors. They exaggerate brightness differences (contrast); therefore, certain features become easier to see. So, when you use a filter, look for brightness changes rather than color changes on the planet or in its clouds.

Manufacturers label color filters along their circumferences. To use one, screw it into the eyepiece's barrel. All eyepiece filters have threads that match the threaded inside barrels of eyepieces.

All color filters work better with larger telescopes. It's a simple rule of light throughput. For example, a #47 (violet) filter used with a 4-inch telescope to see cloud features on Venus just doesn't work. The filter transmits only 3 percent of the light hitting it. However, the same filter used with a 12-inch scope easily reveals features.

Color filter	Transmission
#8 Light yellow	83 percent
#11 Yellow-green	78 percent
#12 Yellow	74 percent
#15 Deep yellow	67 percent
#21 Orange	46 percent
#23A Light red	25 percent
#25A Red	14 percent
#38A Dark blue	17 percent
#47 Violet	3 percent
#56 Light green	53 percent
#58 Green	24 percent
#80A Blue	30 percent
#82A Light blue	73 percent

Explore Saturn's features


South polar region
South south temperate zone
South south temperate belt
South temperate zone
South temperate belt
South tropical zone
South equatorial belt
Equatorial zone south
Equatorial band
Equatorial zone north
North equatorial belt
North tropical zone
North temperate belt
North temperate zone
North north temperate belt
North north temperate zone
North polar region
C ring
B ring
A ring
F ring
Encke Division
Cassini Division

SATURN'S FEATURES DON'T STAND OUT AS WELL as those of Jupiter, but careful examination reveals a wealth of belts and zones. Saturn's ring system also divides into many individual rings, four of which amateur telescopes can discern. *ASTRONOMY*: ROEN KELLY

satellite moves through Jupiter's shadow. An occultation occurs when the satellite disappears behind Jupiter's disk.

A transit occurs when a moon moves in front of Jupiter. Best views come when the satellites appear against Jupiter's dark belts.

A shadow transit occurs when a moon's shadow crosses Jupiter's disk. Shadows appear as small black dots through any telescope.

Observing Saturn

To observe Saturn, first spot the Cassini Division, a dark gap between Saturn's two brightest rings. Through an 8-inch scope, note the rings' brightnesses, color differences, and textures.

Markings on Saturn's disk are subtle. Note any bright or dark spots compared to the belt or zone they're in. From night to night, these features may change position.

Saturn's zones appear off-white, slate-gray, or yellow. Saturn's belts look bluish-gray, brown, and red. Such features stand out well through red, orange, or yellow filters. Occasional bright patches look best through a #58 (green) filter. Highlight the rings using a #56 (light green) or #80A (light blue) filter.

Observing Uranus

Uranus' atmosphere is usually a featureless haze. Observers first reported details in 1870. Since then, other observers have seen markings and belts. Through a small telescope, greenish Uranus appears as a slightly elliptical disc because of its rapid rotation. Uranus moves slowly. It takes the planet about 44 days to move the width of the Full Moon.

Observing Neptune

To the amateur astronomer with binoculars or a telescope, Neptune is no problem to find. At opposition, it displays a small blue disk, which shines at about magnitude 7.7.

Even a large telescope won't reveal much detail on Neptune, although you will see its largest moon, Triton, which shines at magnitude 13.5. The thrill of observing Neptune comes when you first spot it through your telescope. Because it lies farther from the Sun than Uranus, Neptune moves more slowly. It takes approximately 85 days for the planet to traverse a Full Moon's span.

Besides a telescope, it doesn't take much to observe the planets. A good way to start is to check out "The sky this month" in each issue of *Astronomy*. Before you know it, you'll have made seven new celestial friends. ◻

Michael E. Bakich *is a senior editor of* Astronomy.

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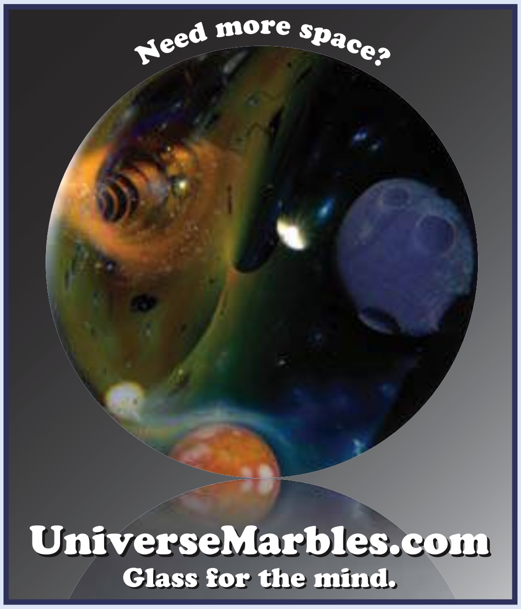

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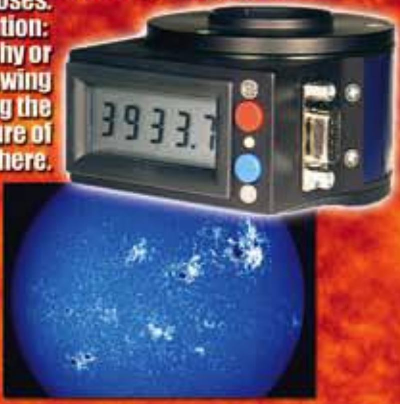

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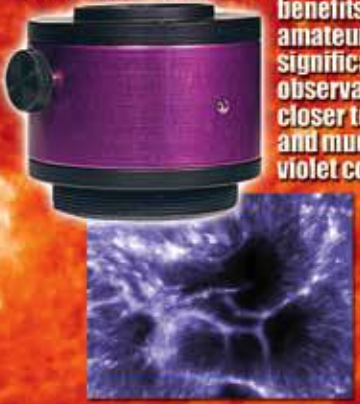

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